Micro-chemical analysis of Arctic char, *Salvelinus alpinus*, otoliths from Ellesmere and Axel Heiberg islands, Nunavut

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ABSTRACT

Babaluk, J.A., Wastle, R.J., and Reist, J.D. 2010. Micro-chemical analysis of Arctic char, *Salvelinus alpinus*, otoliths from Ellesmere and Axel Heiberg islands, Nunavut. Can. Data Rep. Fish. Aquat. Sci. 1225: xiii + 120 p.

Scanning proton microprobe analysis was used to determine the distribution of strontium (Sr) and zinc (Zn) in otoliths of Arctic char, *Salvelinus alpinus*, from seven lakes in Quttinirpaaq National Park, Ellesmere Island, Nunavut, two lakes outside the park on Ellesmere Island, and a lake on adjacent Axel Heiberg Island. Laser ablation inductively coupled-mass spectrometry analysis was also used to determine the distribution of Sr and Zn in otoliths of Arctic char from some of the lakes.

Key words: Arctic char; Buchanan Lake; Lake Hazen; Lake Tuborg; laser ablation inductively coupled-mass spectrometry; micro-PIXE; otolith microchemistry; Quttinirpaaq National Park; scanning proton microprobe.

RÉSUMÉ

Babaluk, J.A., Wastle, R.J., and Reist, J.D. 2010. Micro-chemical analysis of Arctic char, *Salvelinus alpinus*, otoliths from Ellesmere and Axel Heiberg islands, Nunavut. Can. Data Rep. Fish. Aquat. Sci. 1225: xiii + 120 p.

Les chercheurs ont utilisé l'analyse par microsonde à protons pour établir la répartition du strontium (Sr) et du zinc (Zn) dans les otolithes de l'omble chevalier (*Salvelinus alpinus*) de sept lacs du parc national Quttinirpaaq sur l'île d'Ellesmere (Nunavut), de deux lacs situés à l'extérieur du parc sur l'île d'Ellesmere, et d'un lac de l'île Axel Heiberg située à proximité. Ils ont également utilisé la spectrométrie de masse à plasma à couplage inductif avec ablation par laser (LA-ICP-MS) pour déterminer la répartition du Sr et du Zn dans les otolithes de l'omble chevalier de certains des lacs.

Mots-clés: omble chevalier; lac Buchanan; lac Hazen; lac Tuborg; spectrométrie de masse à couplage inductif avec ablation par laser (LA-ICP-MS), micro-PIXE; microchimie des otolithes; parc national Quttinirpaaq; microsonde à protons.

INTRODUCTION

A basic understanding of the biology and diversity of the Arctic char, *Salvelinus alpinus*, the only freshwater fish species in the Canadian High Arctic (Scott and Crossman 1973) is fundamental for long-term conservation and management for the species (e.g., Parks Canada 1994). Although Arctic char is the sole species present, it exhibits great diversity at a number of levels below that of species including: a) life history type (e.g., anadromous or non-anadromous), b) ecological type (e.g., pelagic or benthic forms), c) trophic type (e.g., planktivore or piscivore), d) evolutionary lineages (e.g., subspecies, biological stocks), and, e) variants within many of the above types (e.g., life history variability). This diversity can be observed through a number of techniques, but is best understood using several complementary approaches such as: a) morphology (e.g., body form and function), b) genetics (e.g., delineation of groups using DNA chemistry), c) stable isotopes and diet (e.g., trophic pattern), d) population dynamics (e.g., age and size structure), and e) otolith microchemistry (e.g., life history types, stock discrimination).

Fisheries and Oceans Canada has been assessing the biology and diversity of Arctic char in the Canadian High Arctic since the 1980s and prior to this, in 1958, a group under the auspices of the Defence Research Board of Canada, collected biological information on the Arctic char in Lake Hazen, Ellesmere Island (Hunter 1960; Johnson 1983). Initial research involved population dynamics (Johnson 1983) and contaminant studies (Muir and Lockhart 1992). Between 1992 and 2008, DFO, in collaboration with Parks Canada, intermittently assessed Arctic char populations within Quttinirpaaq National Park (hereafter Park), formerly Ellesmere Island National Park Reserve (e.g., Reist et al. 1995; Babaluk et al. 1997, 2007). Other researchers have also contributed to the understanding of Arctic char in the area either directly (Parker and Johnson 1991) or indirectly (Lewis et al. 2007).

Otoliths (small, paired structures found in the inner ear of all teleost fish including Arctic char) are used for sensing, orientation, and acceleration. They are composed mainly of a calcium carbonate (aragonite) in a protein matrix but trace elements similar to calcium (Ca), such as strontium (Sr) and zinc (Zn) can be incorporated into or replace Ca in the otolith (Degens et al. 1969). The Ca and most trace elements are derived mainly from the waters that the fish inhabits (Ichii and Mugiya 1983). Otoliths do not undergo resorption during the life of the fish (Simkiss 1974) and thus can provide an elemental record of the water chemistry (environment) associated with fish life history.

Sea water contains, on average, 8.0 $mg \cdot L^{-1}$ Sr whereas freshwater contains, on average, 0.1 $mg \cdot L^{-1}$

Sr (Rosenthal et al. 1970). Local freshwater Sr concentrations also can vary. For example, in Quttinirpaaq National Park lakes, Sr concentrations range from 0.033-0.329 $mg \cdot L^{-1}$ (Babaluk et al. 1999). Sr concentrations in otoliths closely reflect environmental levels of Sr (Babaluk et al. 1998) and thus provide information on the types of environments occupied at particular times of life. This can be used to reconstruct life history and also to differentiate specific environments occupied.

Previous studies using scanning proton microprobe analysis (SPMA) [also called micro-proton-induced X-ray emission (micro-PIXE) analysis] of Sr in Arctic char otoliths showed that differences in Sr concentrations can retrospectively indicate anadromous behaviour or, in the case of Lake Hazen Arctic char, indicate non-andromous behaviour (Babaluk et al. 1997). Another SPMA study showed that Zn has a typically oscillatory variation that corresponds to the annular structure of Arctic char otoliths (Halden et al. 2000). Incorporation of Zn is linked to nutrient uptake in the fish so the concentration of Zn in the otolith must, in part, be a proxy for nutrient availability in the environment and perhaps the productivity of a particular environment. Zinc is an important trace nutrient that is necessary for the development of fish gonads (Lall 1989). The onset of sexual maturity and the development of gonads will likely alter the metabolic distribution of Zn and this may be recorded in the otolith.

In a previous report, we presented a summary of SPMA-derived otolith micro-chemical data from Arctic char populations in Quttinirpaaq National Park (Babaluk et al. 2002). In this report, we present additional SPMA-derived otolith microchemistry data from the Quttinirpaaq National Park Arctic char as well as data from two lakes on Ellesmere Island located outside Quttinirpaaq National Park and one lake on adjacent Axel Heiberg Island. We also present otolith micro-chemical data from a subset of these Arctic char that was determined by laser ablation-inductively coupled-mass spectrometry (LA-ICP-MS) analysis. Both instruments are used to measure trace elements in otoliths (Campana et al. 1997).

MATERIALS AND METHODS

STUDY AREA AND SAMPLE COLLECTION

Ellesmere Island

Quttinirpaaq National Park (82° 13' N, 72° 13'W) is located at the northern end of Ellesmere Island,

Nunavut (Fig. 1). The Park, with an area of 37 775 km^2, is the second largest national park in Canada and is described in detail in Parks Canada (1994). There are relatively few lakes in the park and the most productive ones are located between Lake Hazen and the eastern coast of the island or along the northern coast (Fig. 1). Lakes from the Park for this study were chosen because they were known to contain populations of Arctic char.

Between 1992 and 2002, we captured Arctic char from seven lakes in the Park (Fig. 1) and collected and analyzed their otoliths: 1) an unnamed lake, hereafter Clements Markham Lake (82° 38' N, 68° 50' W) in 2001 and 2002 (n = 10); 2) Lake Alexandra (81° 46' N, 65° 32' W) in 1995 (n = 6); 3) Lake Hazen (81° 50' N, 70° 25' W) in 1992 and 2001 (n = 16); 4) an unnamed lake, hereafter Lower Beaufort Lake (81° 54' N, 63° 17' W) in 2001 (n = 9); 5) an unnamed lake, hereafter Rambow Hill Lake (83° 00' N, 75° 27' W) in 2002 (n = 8); 6) Turnabout Lake (81° 54' N, 68° 16' W) in 2001 (n = 5); and 7) an unnamed lake, hereafter Upper Beaufort Lake (81° 54' N, 63° 16' W) in 2001 (n = 10).

Clements Markham and Rambow Hill lakes were earlier, provisionally (unofficially) named lakes G and A, respectively by Hattersley-Smith et al. (1970) and other researchers use these names, for at least Lake A (Belzile et al. 2001). When we sampled the lakes and until very recently, we were unaware of the previous work and assigned our own unofficial names. As we have our own alphabetic series of lakes (A-H) in Quttinirpaaq National Park (Babaluk et al. 2007, 2009), for this and subsequent publications we will continue to use our names.

Lake H (80° 51' N, 80° 52' W) is located at the head of the eastern arm of Borup Fiord on Ellesmere Island (Fig. 1). The lake is not named on topographic maps but was provisionally named by Parker and Johnson (1991). It should not be confused with our Lake H (see above, Babaluk et al. 2009). A detailed description of Parker and Johnson's Lake H, Arctic char in the lake, and the Borup Fiord area, in general, is given by Parker and Johnson (1991).

The lake was revisited in 1991 (H.H. Parker, Gloucs, U.K., pers. comm. 1991) and otoliths from Arctic char (n = 10) collected during the 1991 expedition were used for our study.

Lake Tuborg (80° 57' N, 75° 35' W) is a large, fiord-type lake on Ellesmere Island at the eastern edge of Greely Fiord (Fig. 1). The lake was formed about 3000 years ago when a glacier advanced and sealed off the inner part of the fiord (Long 1967). The resulting lake contains sea water at depth, trapped at the time of the glacial advance (Hattersley-Smith and Serson 1964). The lake

contains 50-60 m of freshwater overlying anoxic marine water (Lewis et al. 2007). Details of lake morphometry and bathymetry are found in Lewis et al. (2007).

While collecting the data that resulted in Lewis et al. (2007), the geoscientists, under our direction, captured Arctic char from Lake Tuborg and collected the otoliths used in this study (2002 and 2003, n = 23).

Axel Heiberg Island

Buchanan Lake (79° 30' N, 87° 30' W) is located on the east side of Axel Heiberg Island at the head of Mokka Fiord (Fig. 1, inset). The lake, located in a steep-walled (400-600 m) valley, is ~11 km long and ranges in width from 1-2 km. Morphometric and bathymetric data on the lake is given in Lockhart et al. (1998). The lake empties into Mokka Fiord by a short (~2.5 km), low-gradient river. Archaeological artifacts found along the river indicate that fishing, most likely for anadromous Arctic char, has taken place in the area (Schledermann 1975).

Arctic char from Buchanan Lake were captured in 1991 as part of a study on contaminants in fish (Braune et al. 1999). Otoliths from 10 of those char were used for our study.

OTOLITH PREPARATION

One of each pair of otoliths was prepared for SPMA or LA-ICP-MS analysis. The otoliths were prepared for SPMA as described in Babaluk et al. (2002). Otoliths for LA-ICP-MS were prepared as for SPMA except that a coat of carbon was not applied (not required).

SCANNING PROTON MICROPROBE ANALYSIS

Scanning proton microprobe analysis was done using the proton microprobe located in the Department of Physics at the University of Guelph, Guelph, ON. Line-scans were run across the otolith section surface from core to edge, perpendicular to annuli. On selected otoliths point analyses, where the proton beam was focussed on three spots within the first annulus, were conducted. The instrument and methodology used are further described in Babaluk et al. (2002). Other details on proton microprobe theory and procedures are provided by Campbell et al. (1995).

LASER ABLATION-ICP-MS ANALYSIS

LA-ICP-MS analyses were done using a Thermo Finnigan Element 2 ICP-MS coupled to a Merchantek LUV 213 Nd:YAG laser located in the Department of Geological Sciences at the University of Manitoba, Winnipeg, MB. Running conditions used to optimize sensitivity and resolution of the annular growth increments in the otoliths included a 30 micron diameter beam traveling at 2 microns·s^{-1}. Calcium as 56 wt% CaO was used as an internal standard, and the external calibration was done using NIST glass 610 with the nominal values reported by Pearce et al. (1997). Line-scans were run across the otolith section surface from core to edge, perpendicular to annuli in time-resolved or scanning mode. Standard analyses were collected prior to each analytical run. Measured trace element concentrations, standard deviations, and detection limits were processed using GLITTER software (van Achterberg et al. 2001) and exported to a Microsoft® Excel spread sheet file.

DATA PRESENTATION

Line-scan data (as distribution profiles) for Sr and Zn for otoliths from Arctic char from lakes in Quttinirpaaq National Park are presented as follows including analytical instrument: Clements Markham Lake (Figs. 2-11, SPMA), Lake Alexandra (Figs. 12-17, SPMA), Lake Hazen (Figs. 18-23, LA-ICP-MS; Figs. 24-33, SPMA), Lower Beaufort Lake (Figs. 34-42, SPMA), Rambow Hill Lake (Figs. 43-50, SPMA), Turnabout Lake (Figs. 51-55, SPMA); and Upper Beaufort Lake (Figs. 56-65, SPMA). Line-scan data for otoliths from Arctic char from other lakes on Ellesmere Island are presented as follows: Lake H (Figs. 66-75, SPMA) and Lake Tuborg (Figs. 76-77, SPMA; Figs. 78-100, LA-ICP-MS). Line-scan data for otoliths from Arctic char from Buchanan Lake on Axel Heiberg Island are presented in Figures 101-110 (SPMA).

Micro-PIXE point analysis data for Sr and Zn for individual Arctic char from Lake H and Buchanan Lake are presented as insets of Figs. 66-75 and Figs. 101-110, respectively. Point analyses (3 per otolith) were conducted within the first annulus of the otolith.

The Sr for otoliths from Arctic char that were analyzed by both the scanning proton microprobe and LA-ICP-MS instrument are very similar in distribution profile and concentration (e.g., Lake Tuborg: Figs. 76 and 77). This was expected as Sr is measured with accuracy and precision by both instruments (Campana et al. 1997). Otolith Zn for the same fish measured by both instruments

showed similar distribution profiles, however, in all cases Zn concentrations as derived by the scanning proton microprobe were greater than those from the LA-ICP-MS (e.g., Lake Tuborg: Figs. 76 and 77). Campana et al. (1997) noted that there was greater variability in otolith Zn depending on the instrument used for analysis.

Fisheries and Oceans Canada (Winnipeg) fish processing number and selected biometric data for each Arctic char analyzed are also presented (Figs. 2-110). Biometric data includes fork length (mm), weight (g), sex, and age (years). Collection of this data is described in Babaluk et al. (2007).

An electronic version of the data is available from the authors c/o Fisheries and Oceans Canada, 501 University Crescent, Winnipeg, Manitoba, R3T 2N6, Canada.

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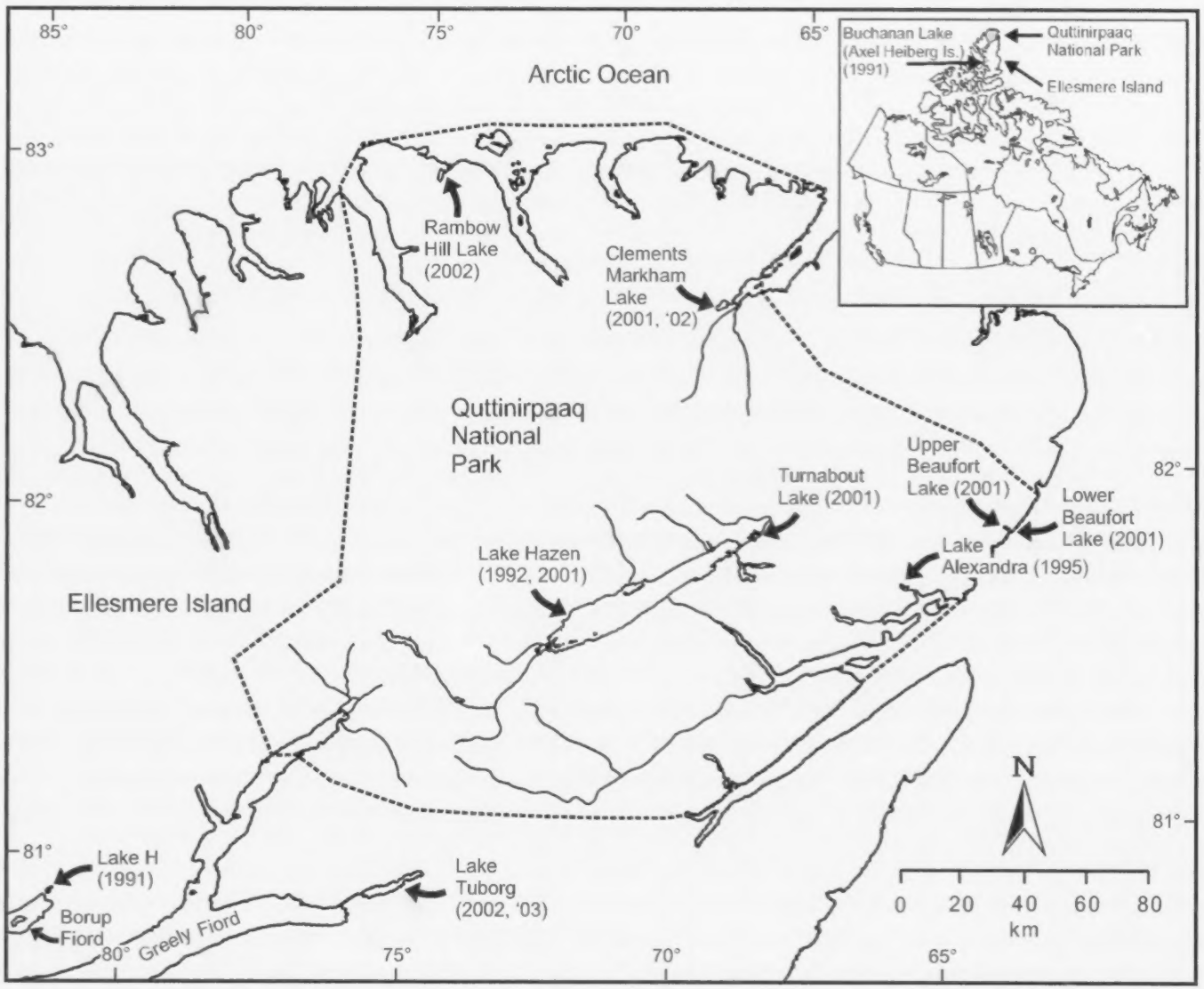

Figure 1. Map of northern Ellesmere Island, Nunavut showing collection locations of Arctic char used for otolith micro-chemical analysis and year fish were collected.

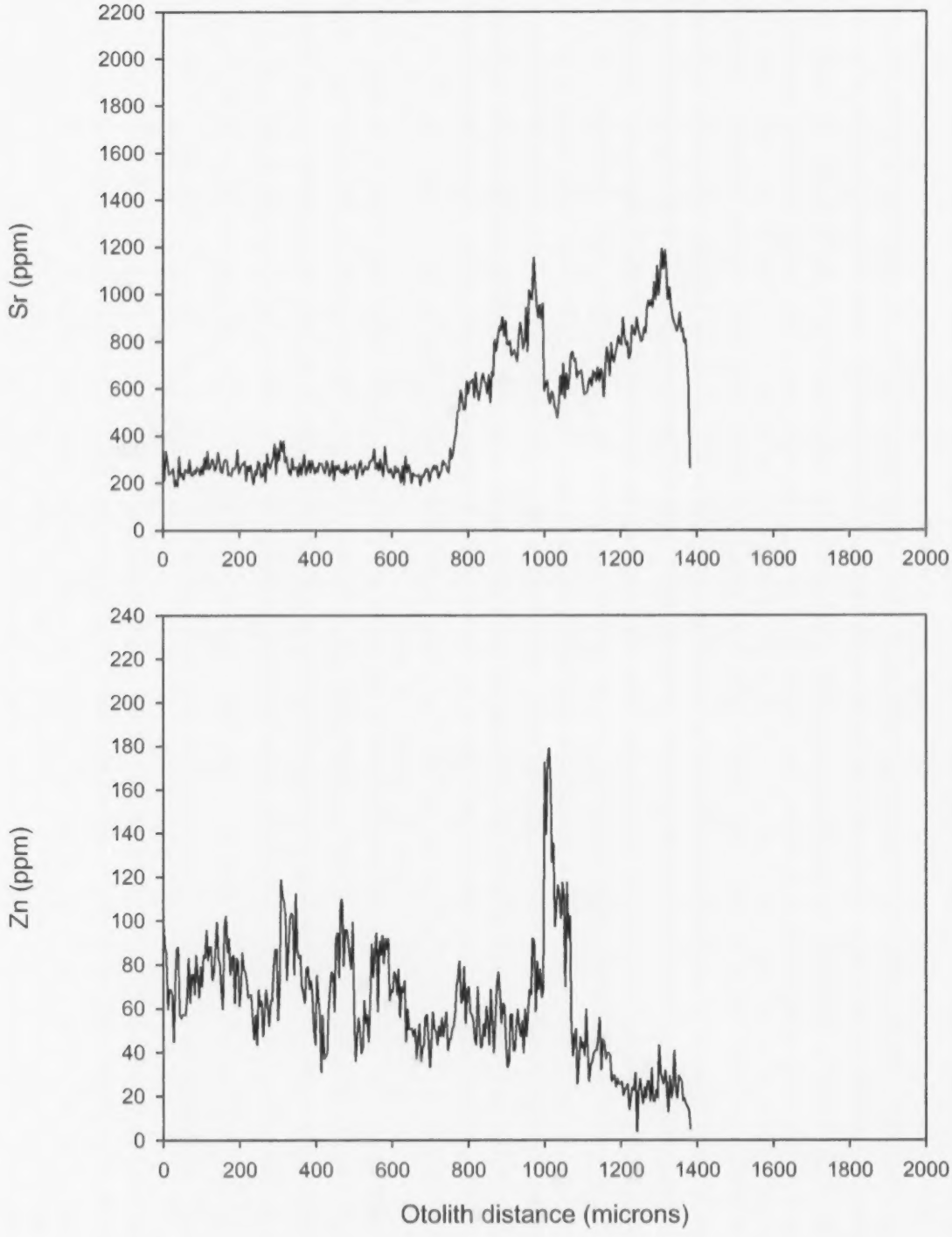

Figure 2. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47317, 430 mm, 840 g, female, 19 yr) caught in Clements Markham Lake, August 10, 2001.

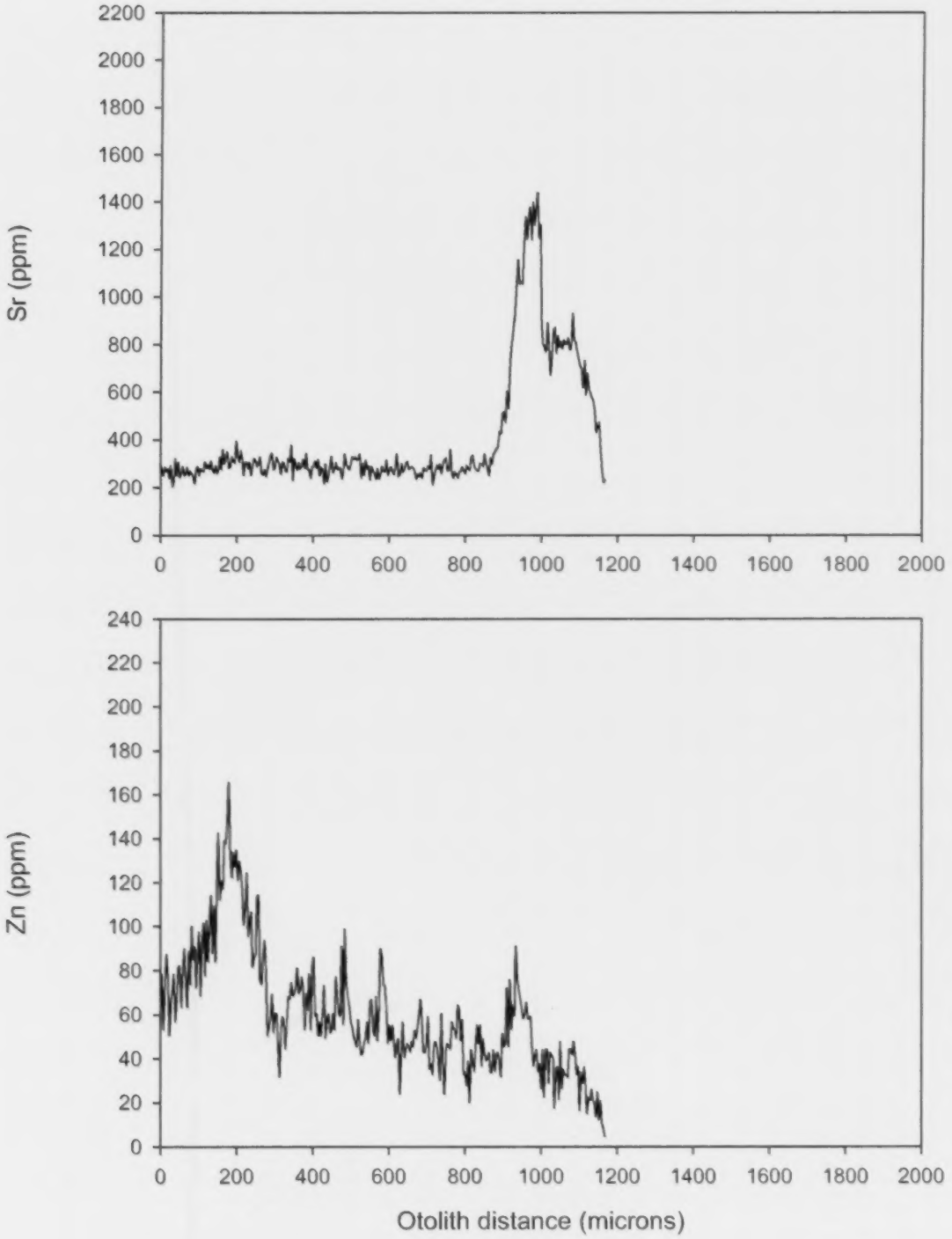

Figure 3. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47318, 353 mm, 390 g, female, 10 yr) caught in Clements Markham Lake, August 10, 2001.

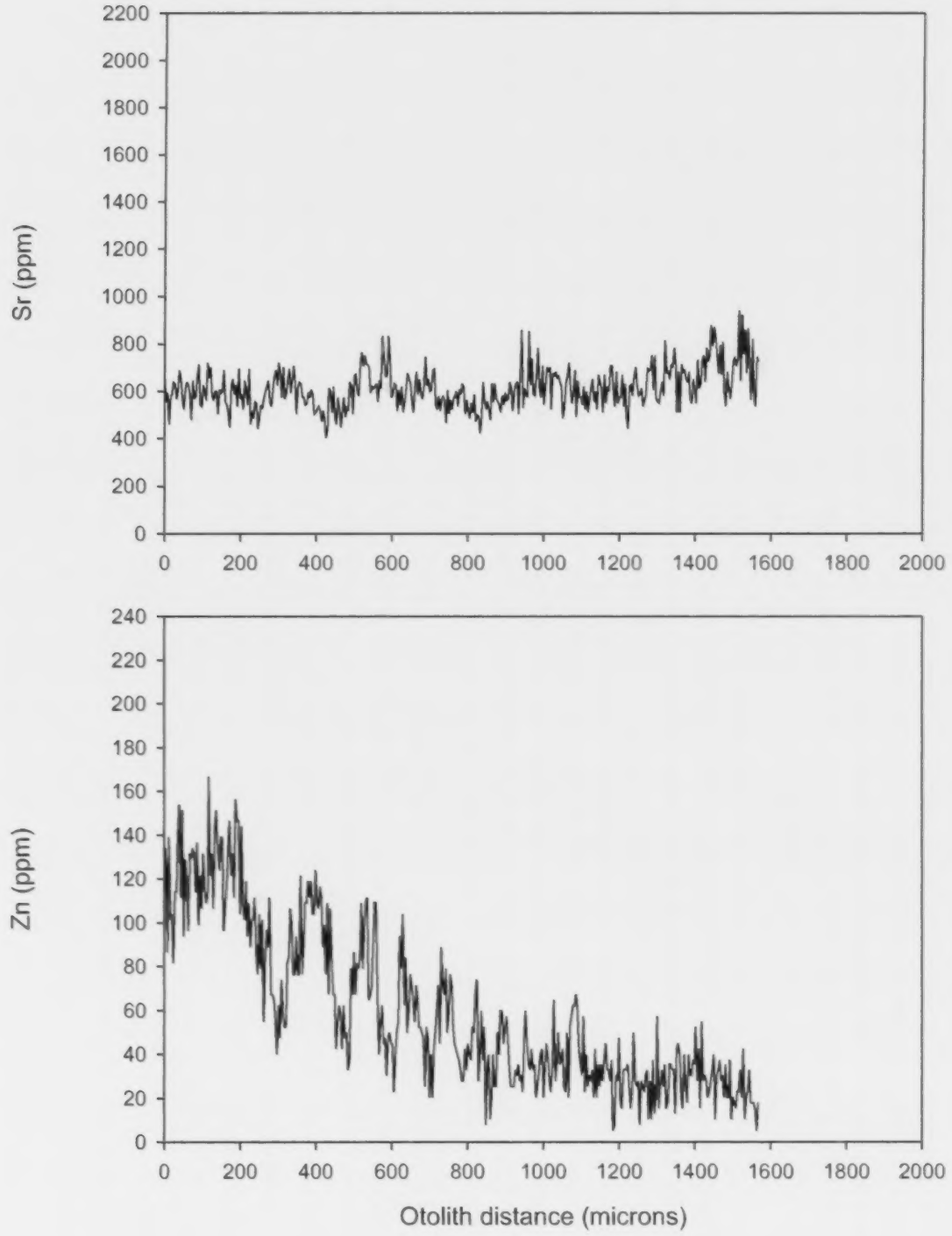

Figure 4. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47319, 410 mm, 690 g, female, 19 yr) caught in Clements Markham Lake, August 10, 2001.

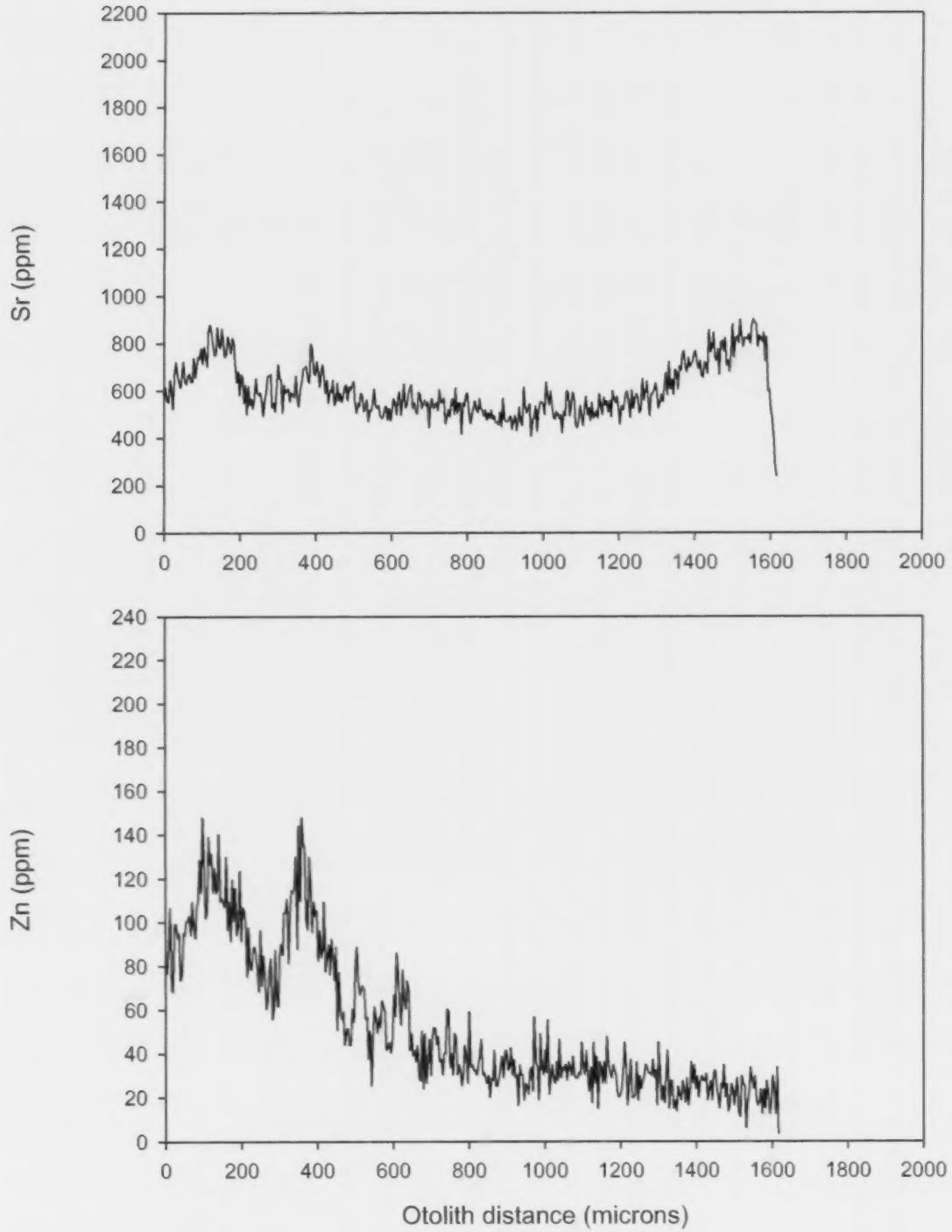

Figure 5. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47320, 413 mm, 510 g, male, 32 yr) caught in Clements Markham Lake, August 10, 2001.

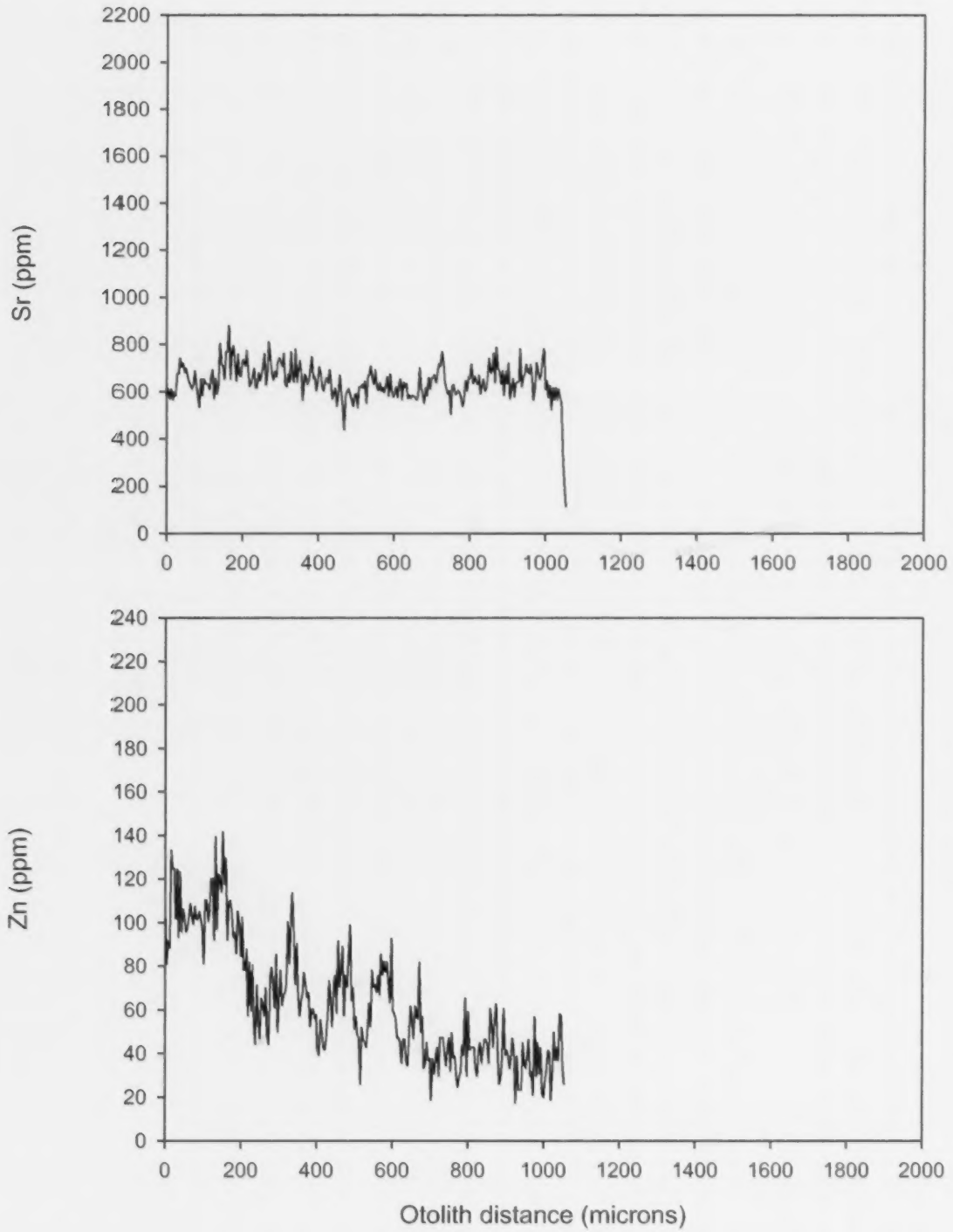

Figure 6. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#49081, 223 mm, 90 g, female, 11 yr) caught in Clements Markham Lake, June 17-18, 2002.

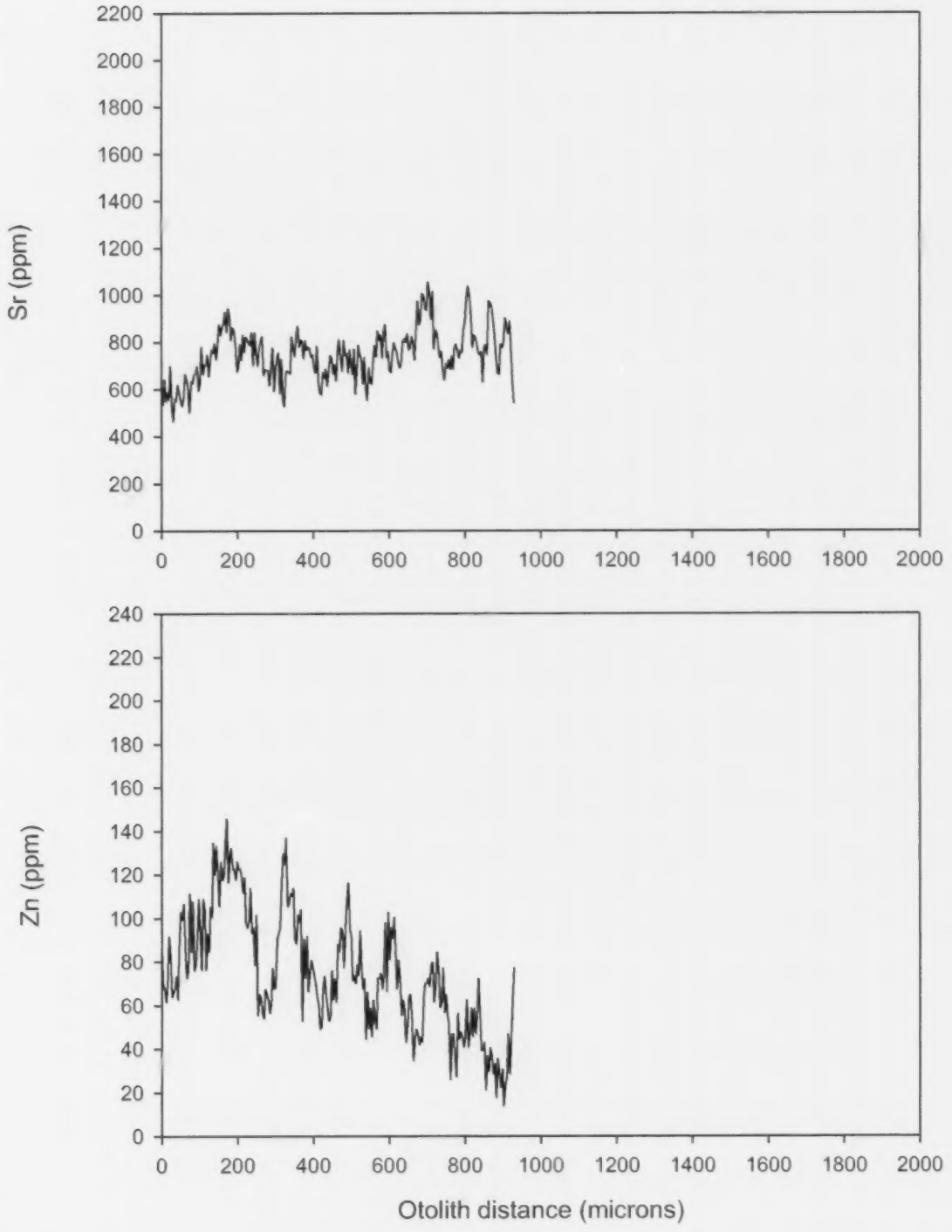

Figure 7. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#49085, 221 mm, 96 g, male, 7 yr) caught in Clements Markham Lake, June 17-18, 2002.

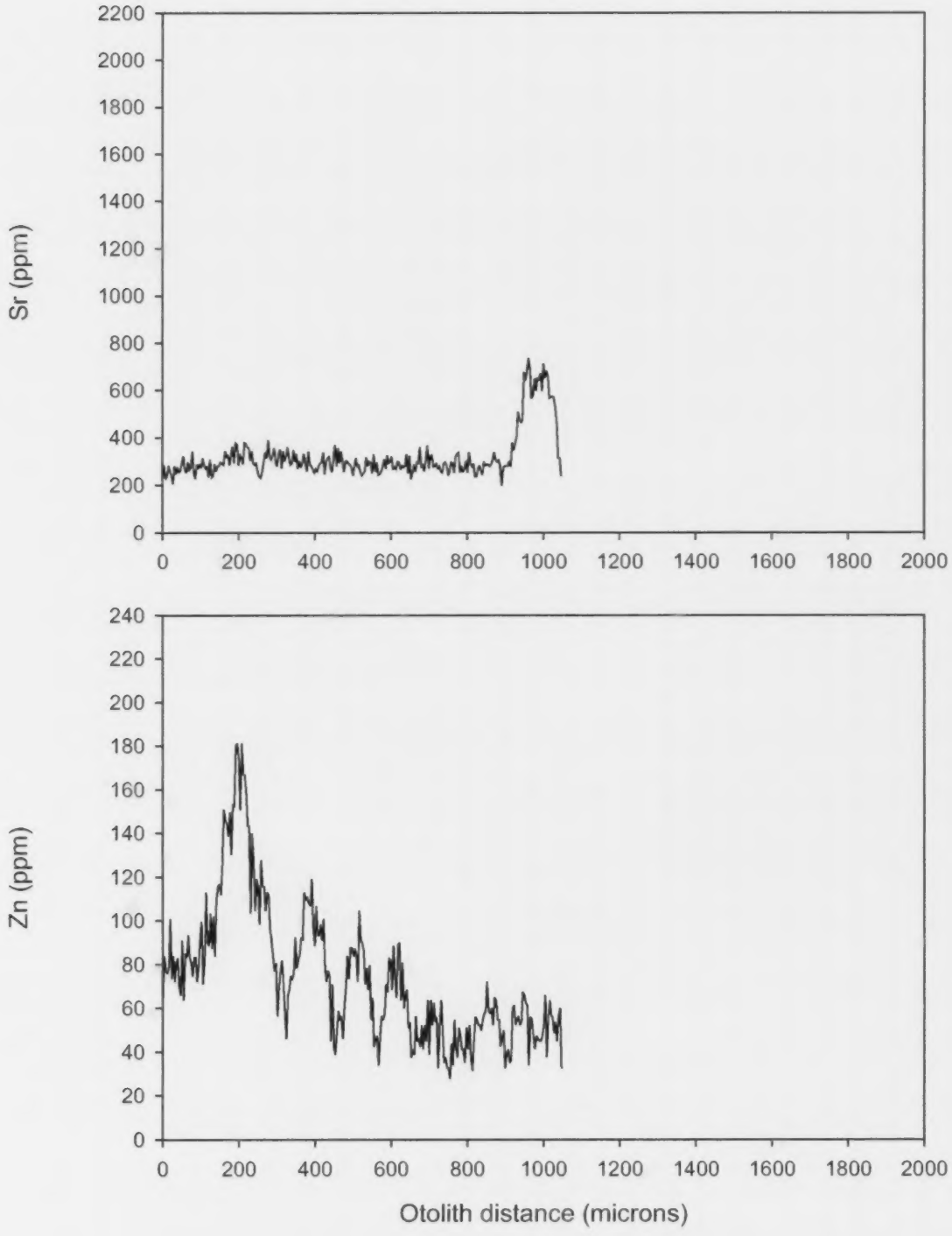

Figure 8. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#49089, 252 mm, 138 g, male, 9 yr) caught in Clements Markham Lake, June 17-18, 2002.

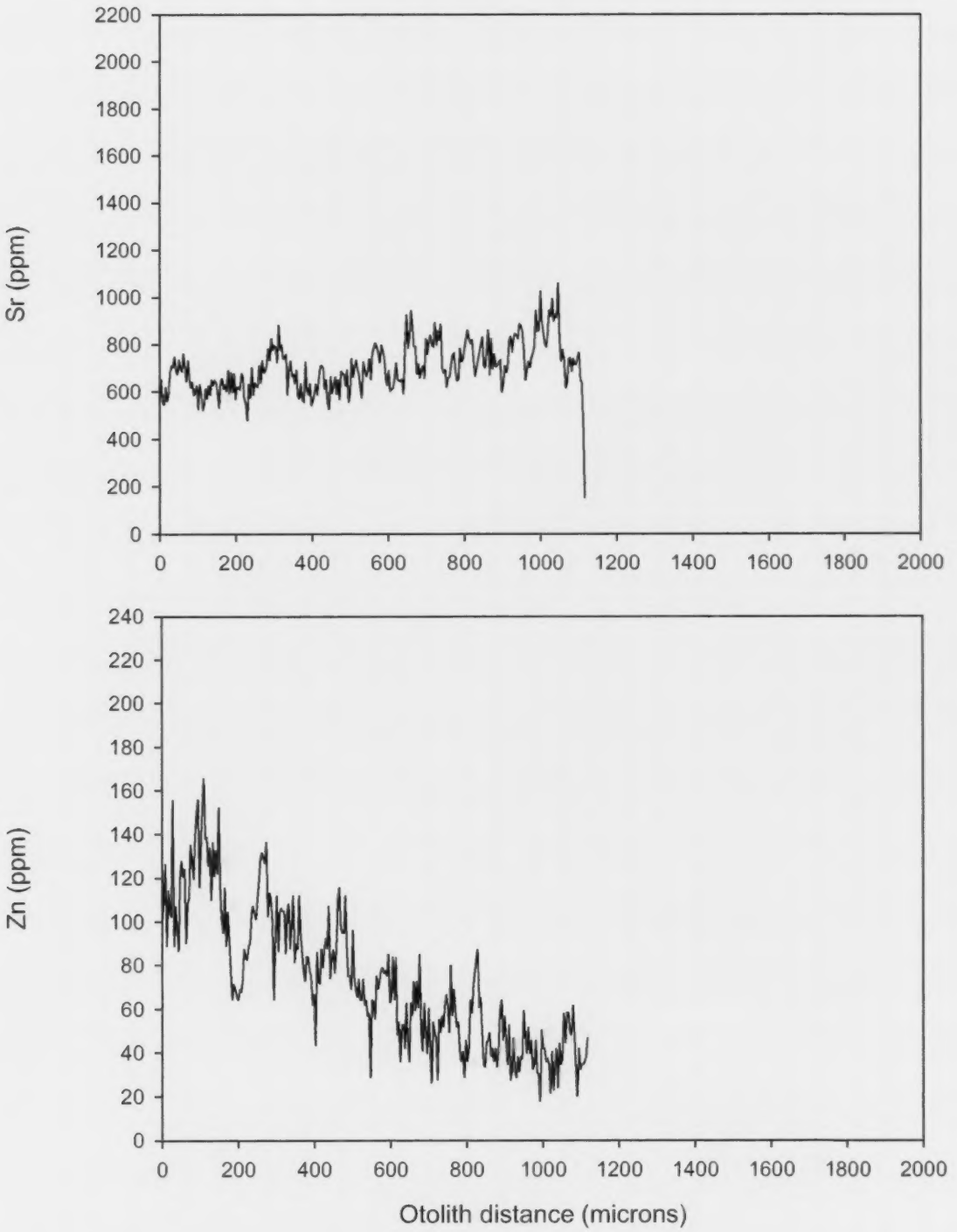

Figure 9. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#49091, 267 mm, 170 g, female, 12 yr) caught in Clements Markham Lake, June 17-18, 2002.

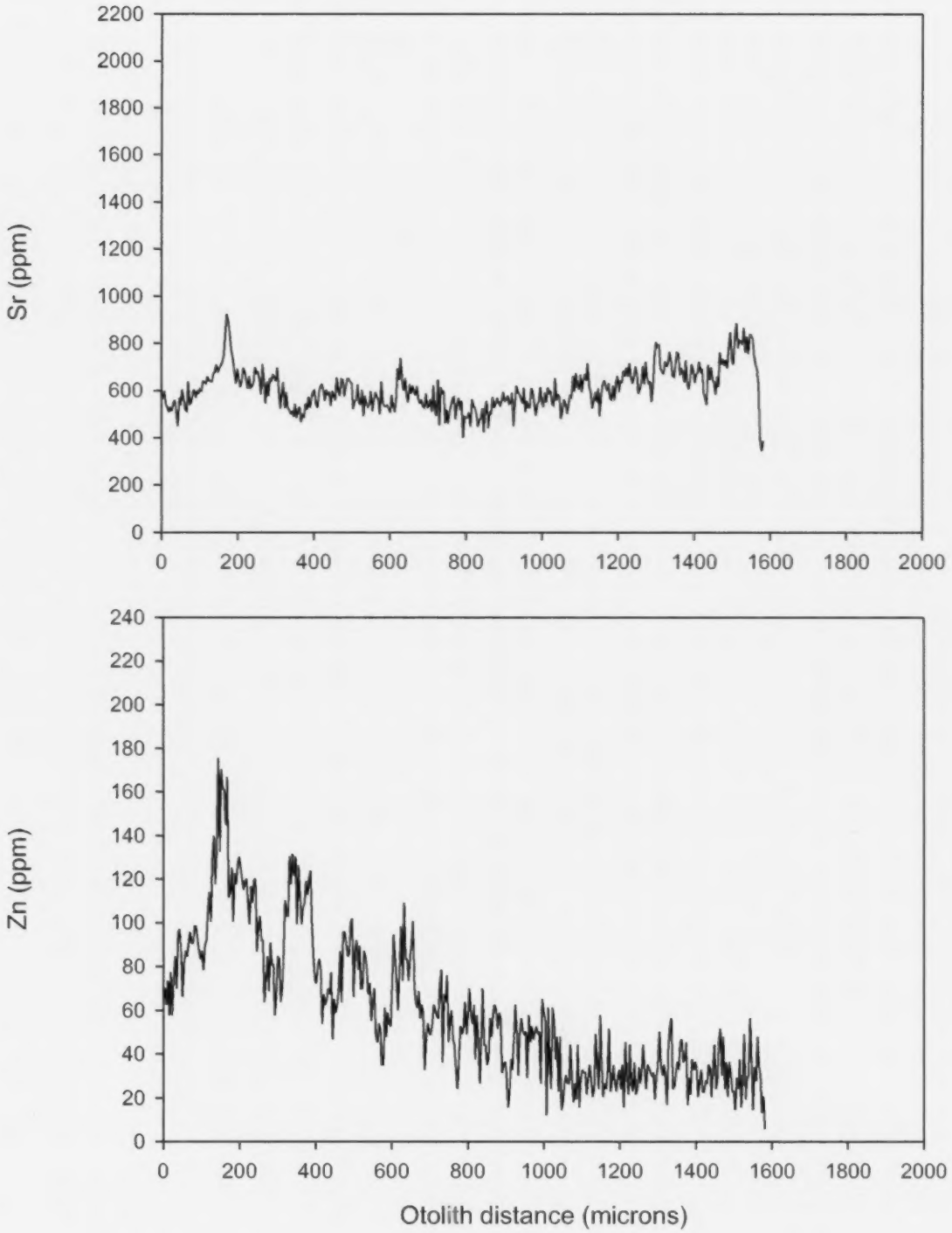

Figure 10. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#49093, 347 mm, 303 g, female, 27 yr) caught in Clements Markham Lake, June 17-18, 2002.

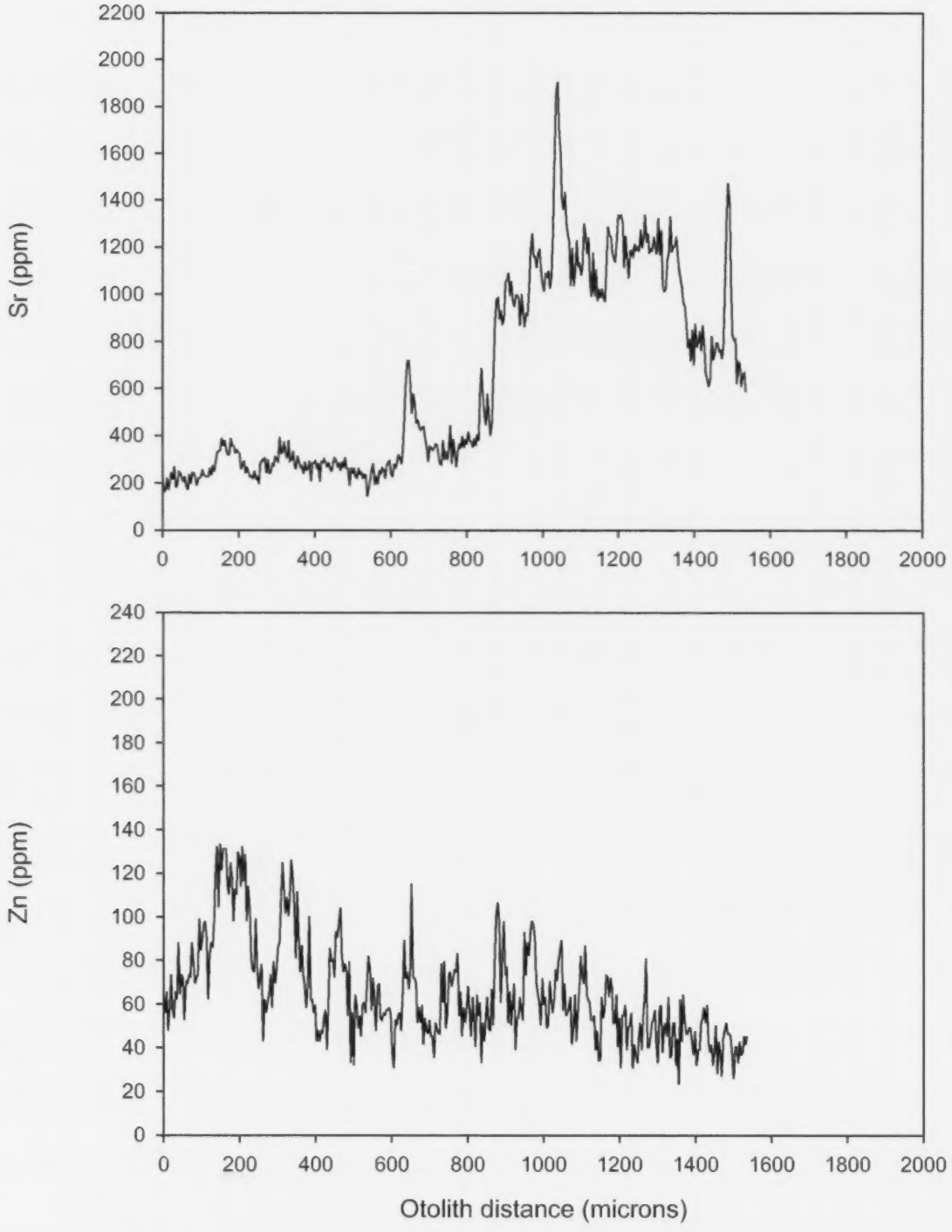

Figure 11. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#49096, 448 mm, 746 g, male, 18 yr) caught in Clements Markham Lake, June 17-18, 2002.

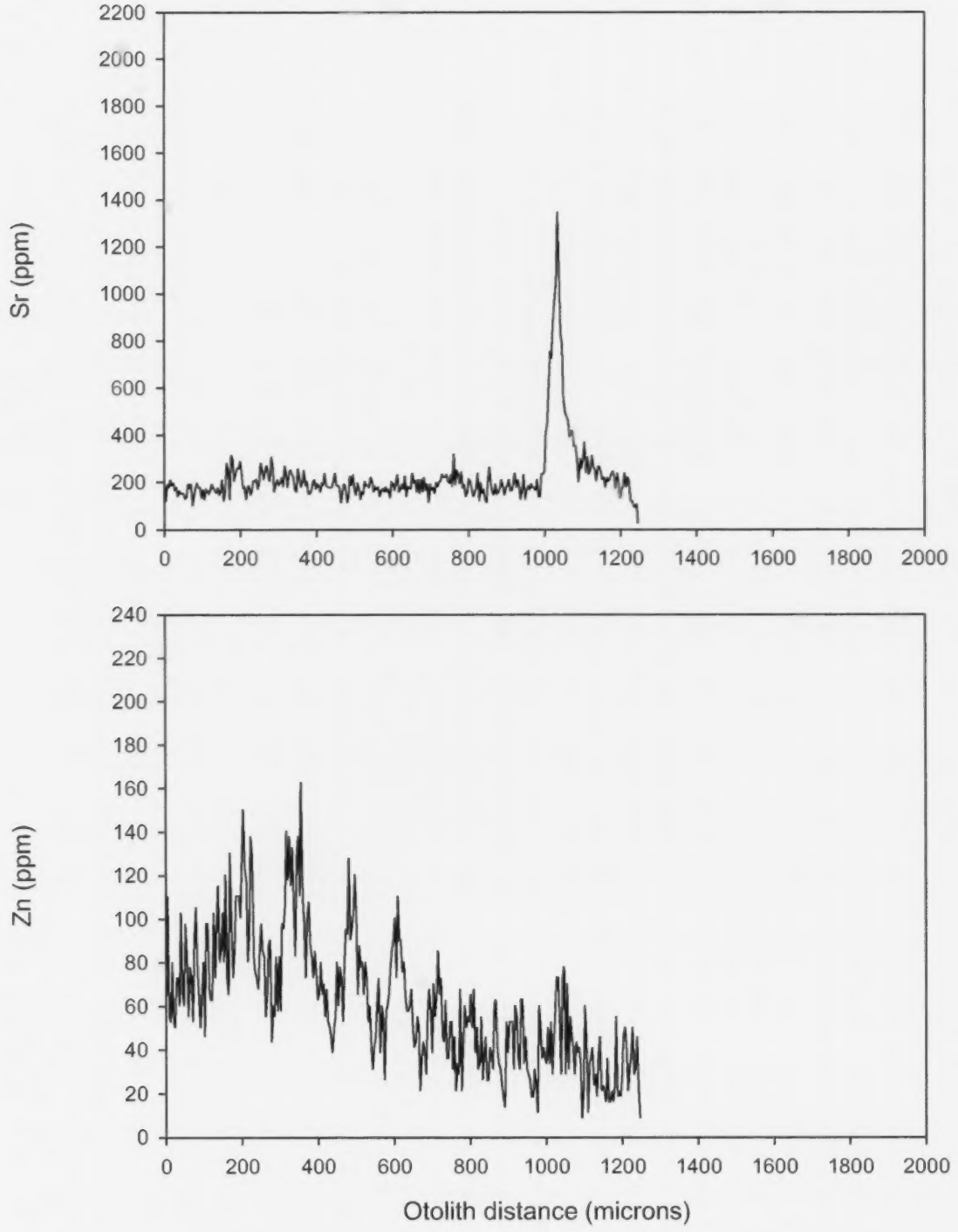

Figure 12. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#42342, 346 mm, 750 g, female, 13 yr) caught in Lake Alexandra, May 11, 1995.

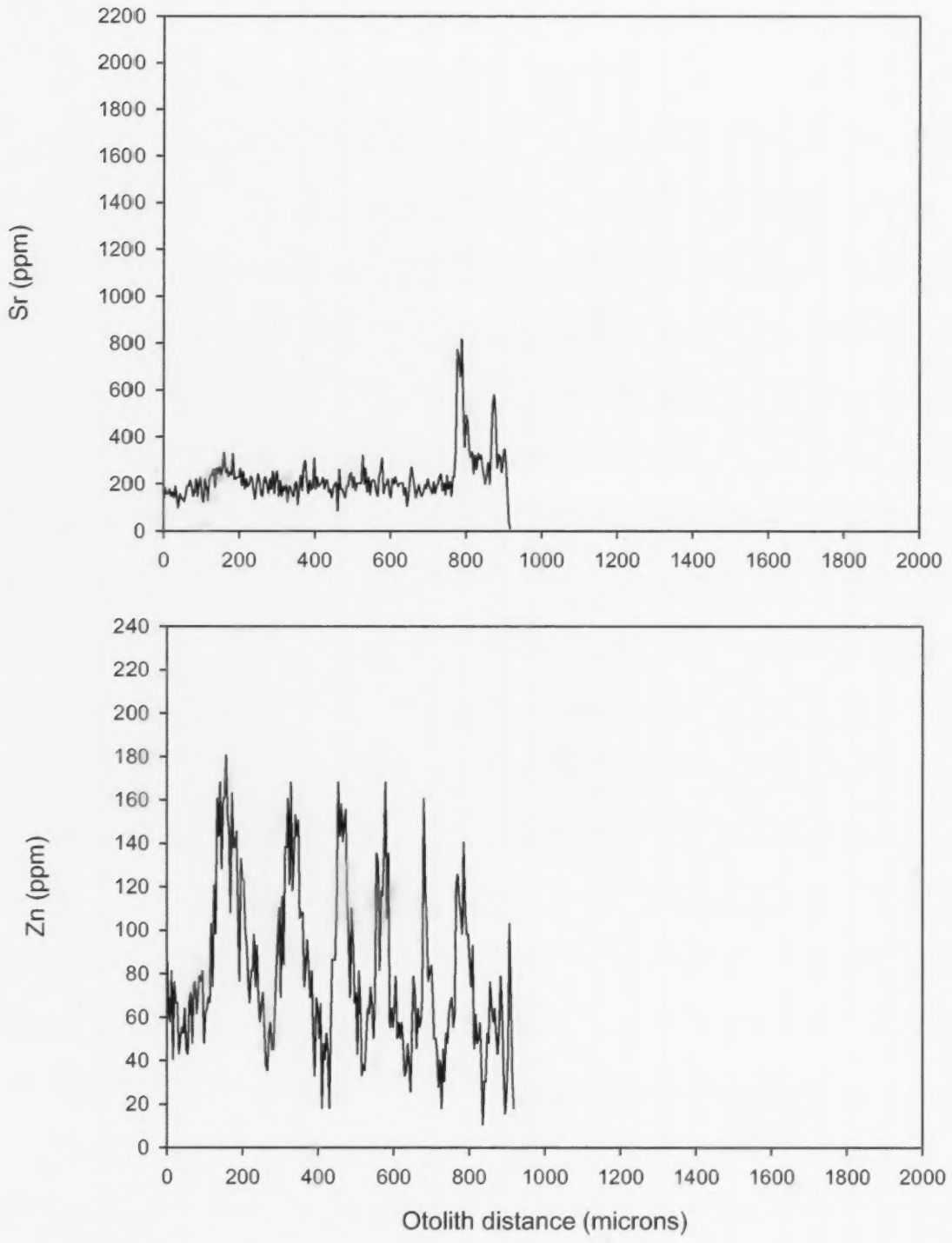

Figure 13. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#42350, 251 mm, 278 g, female, 7 yr) caught in Lake Alexandra, May 11, 1995.

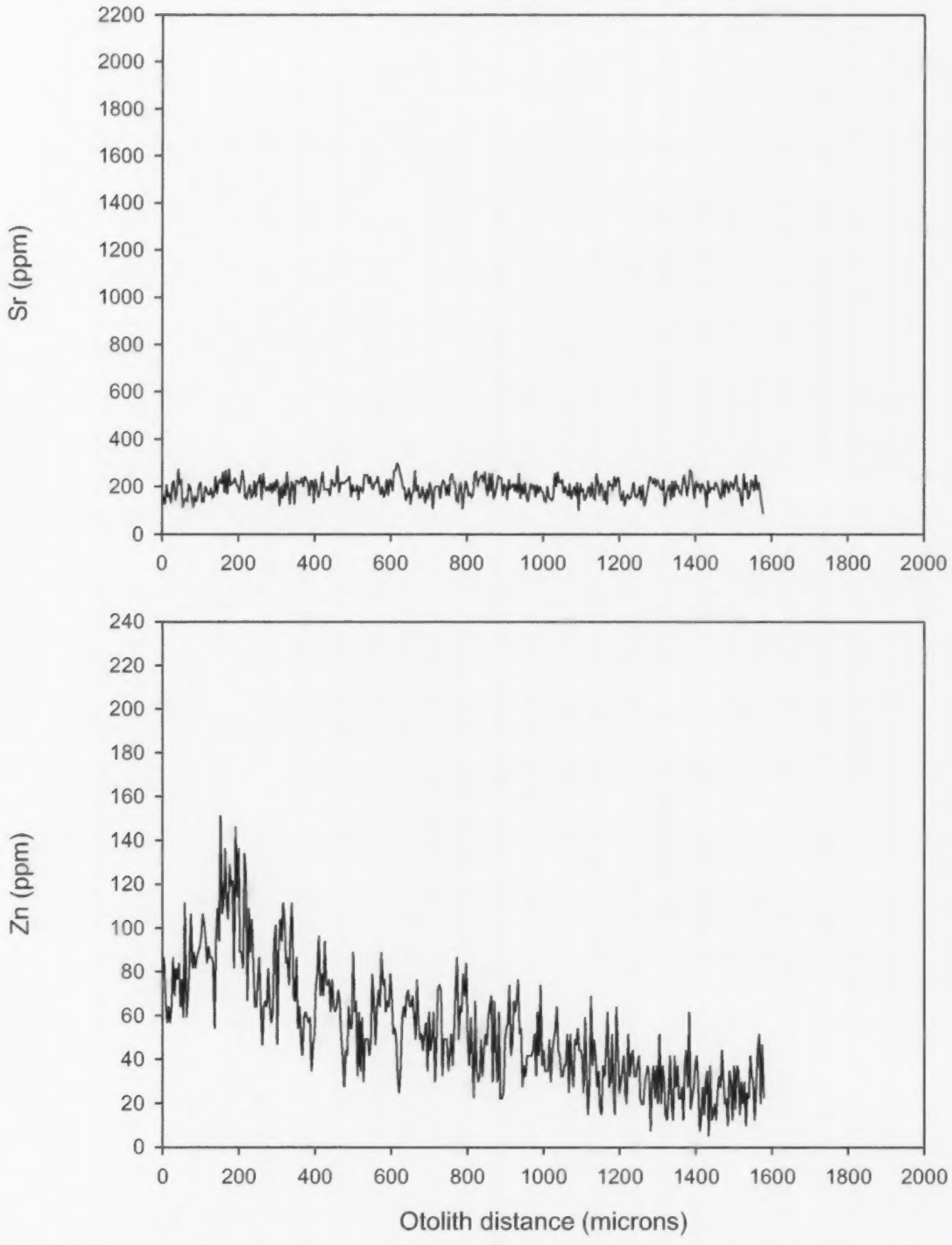

Figure 14. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#42351, 336 mm, 575 g, female, 28 yr) caught in Lake Alexandra, May 11, 1995.

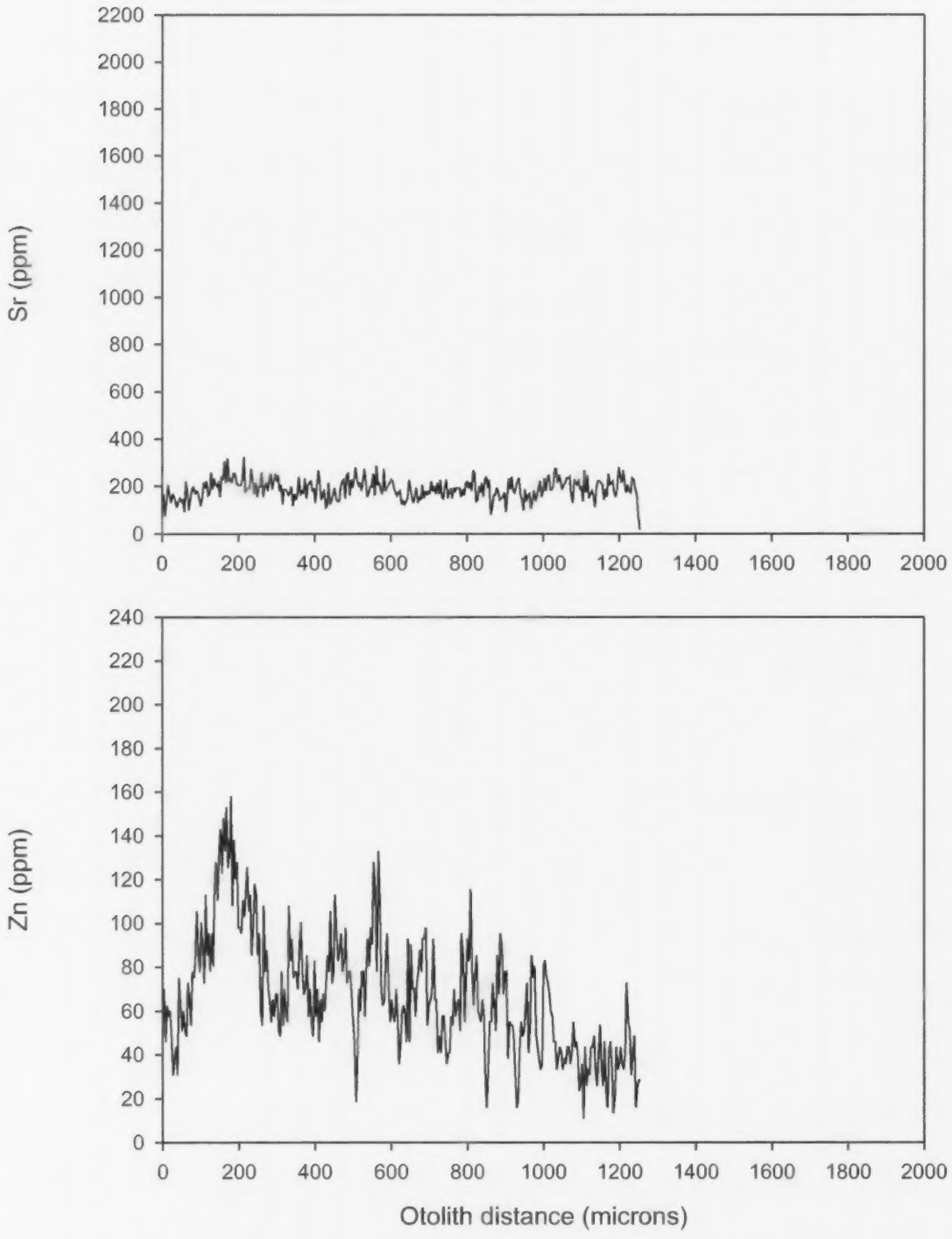

Figure 15. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#42556, 333 mm, 325 g, female, 13 yr) caught in Lake Alexandra, May 11, 1995.

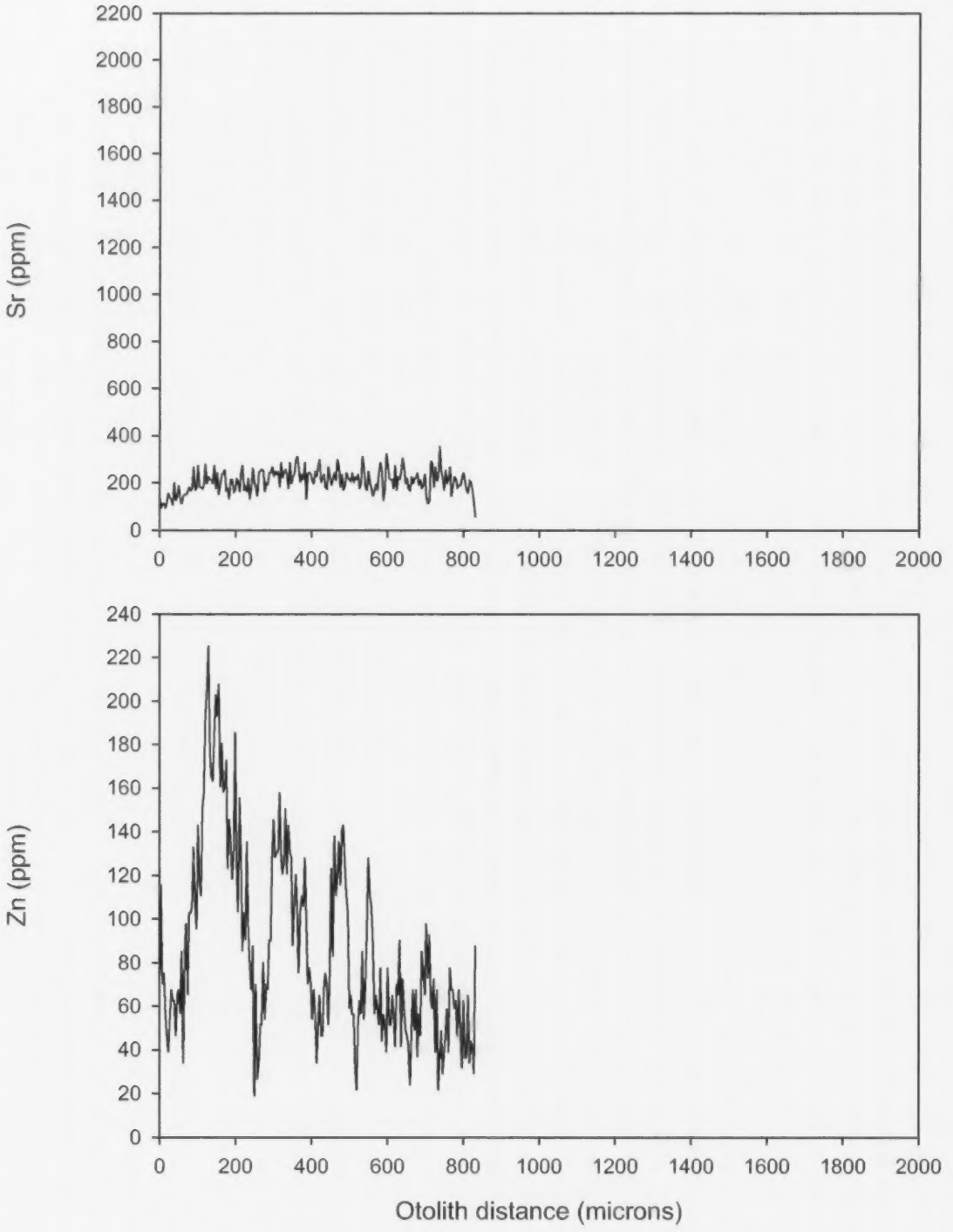

Figure 16. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#42562, 191 mm, 56 g, female, 6 yr) caught in Lake Alexandra, May 11, 1995.

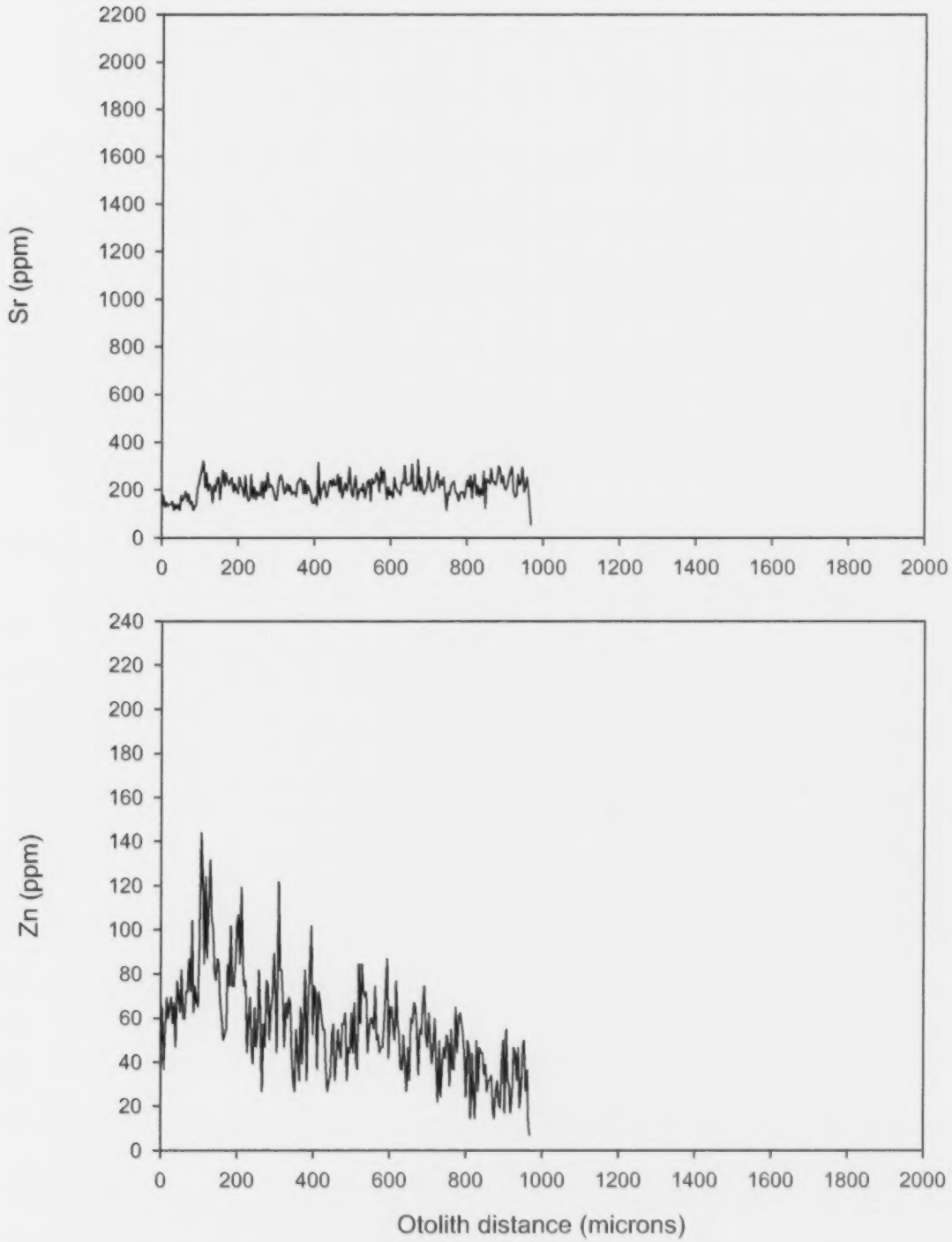

Figure 17. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#42780, 252 mm, no weight taken, male, 9 yr) caught in Lake Alexandra, May 11, 1995.

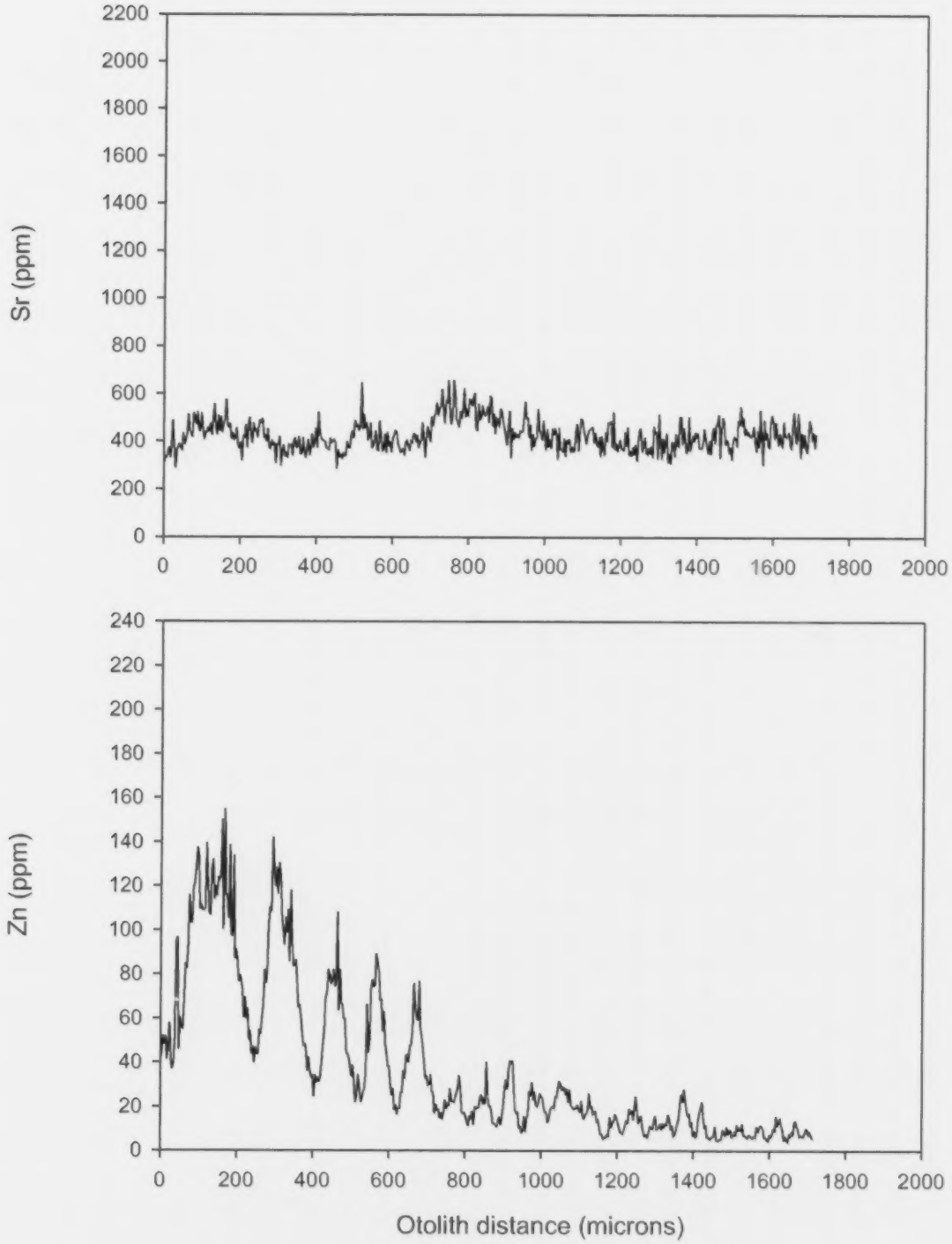

Figure 18. Strontium (top) and zinc (bottom) profiles from an LA-ICP-MS line-scan of an otolith from an Arctic char (#38263, 501 mm, 925 g, female, 22 yr) caught in Lake Hazen, June 16, 1992.

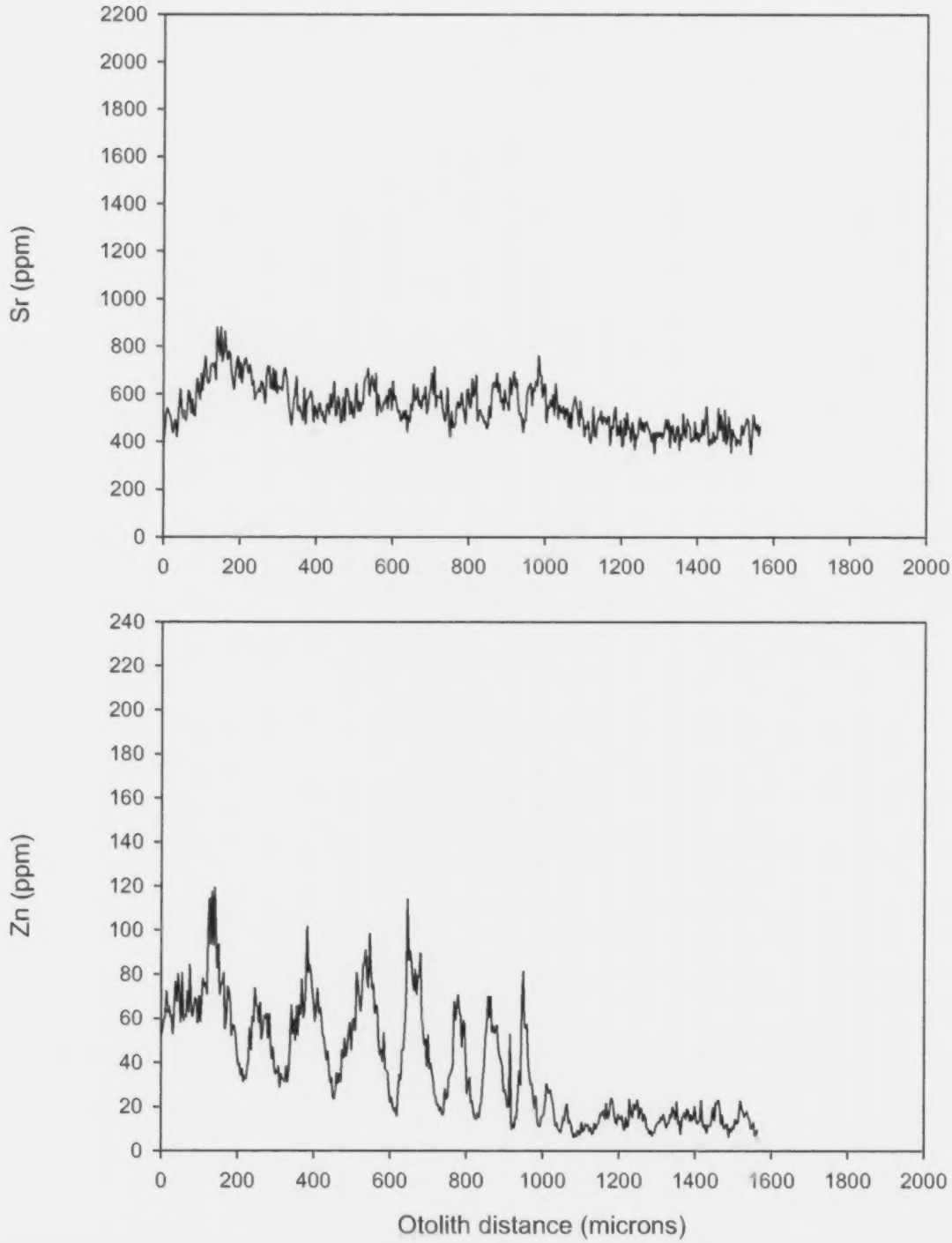

Figure 19. Strontium (top) and zinc (bottom) profiles from an LA-ICP-MS line-scan of an otolith from an Arctic char (#38281, 489 mm, 1086 g, male, 17 yr) caught in Lake Hazen, June 19, 1992.

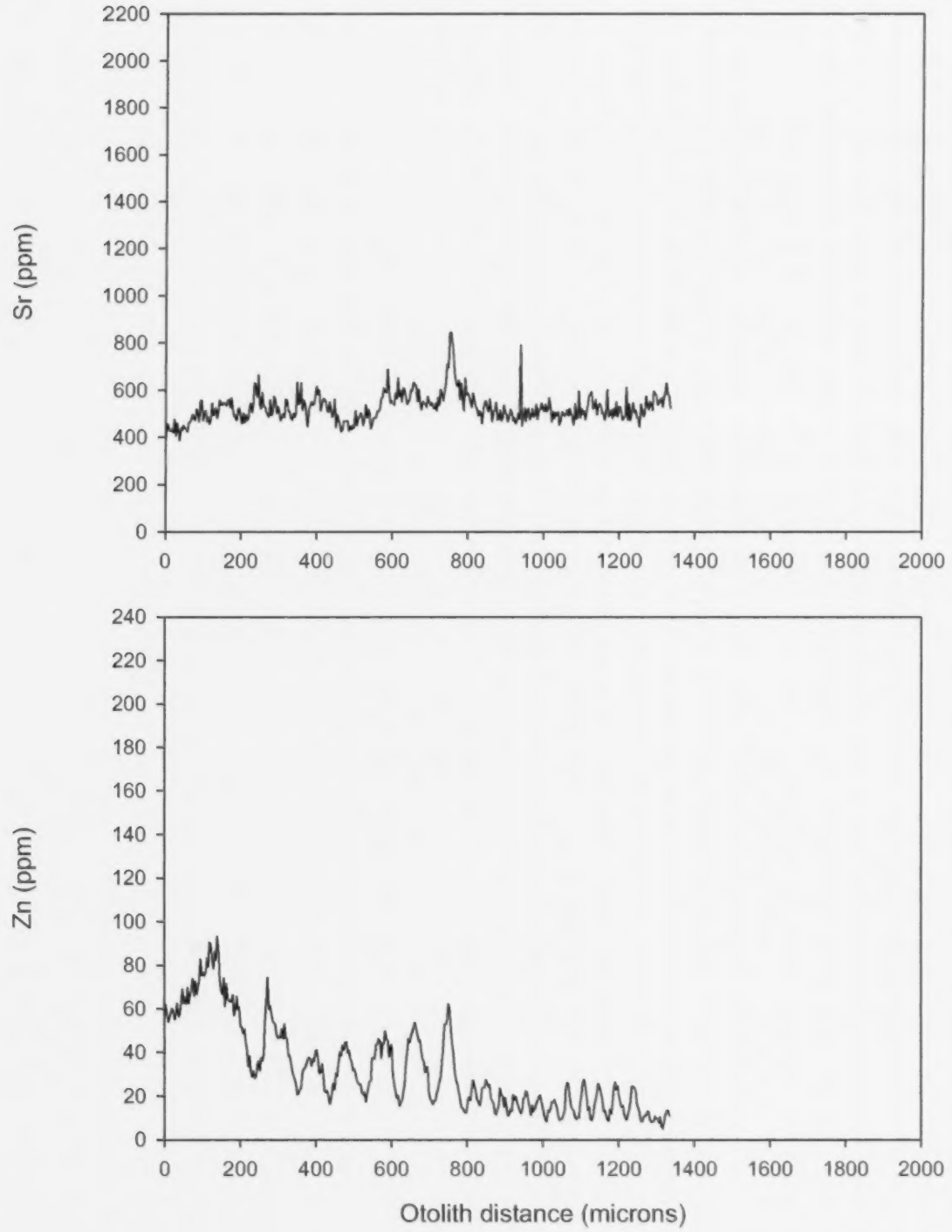

Figure 20. Strontium (top) and zinc (bottom) profiles from an LA-ICP-MS line-scan of an otolith from an Arctic char (#38297, 356 mm, 476 g, male, 18 yr) caught in Lake Hazen, June 18, 1992.

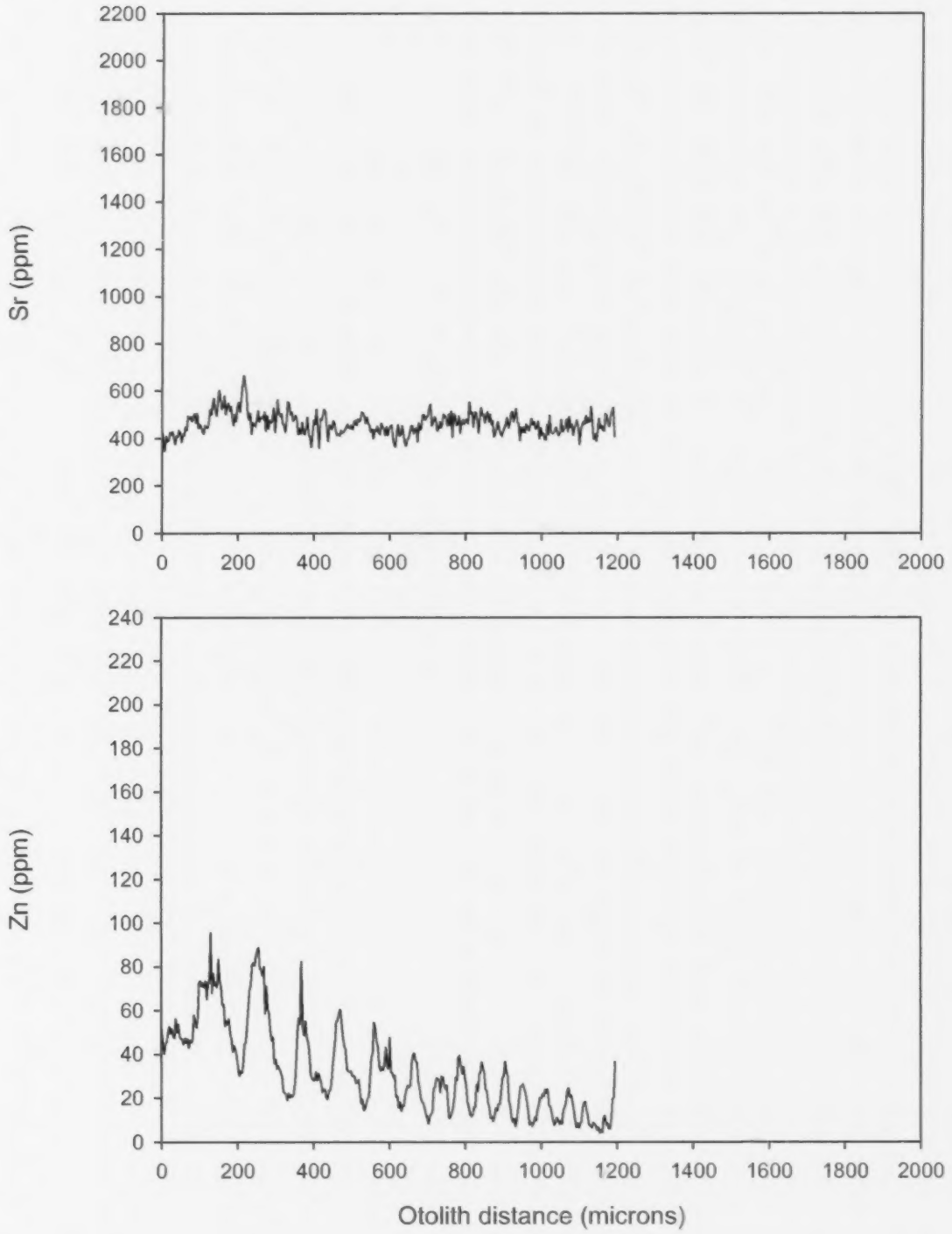

Figure 21. Strontium (top) and zinc (bottom) profiles from an LA-ICP-MS line-scan of an otolith from an Arctic char (#38298, 314 mm, 283 g, female, 15 yr) caught in Lake Hazen, June 18, 1992.

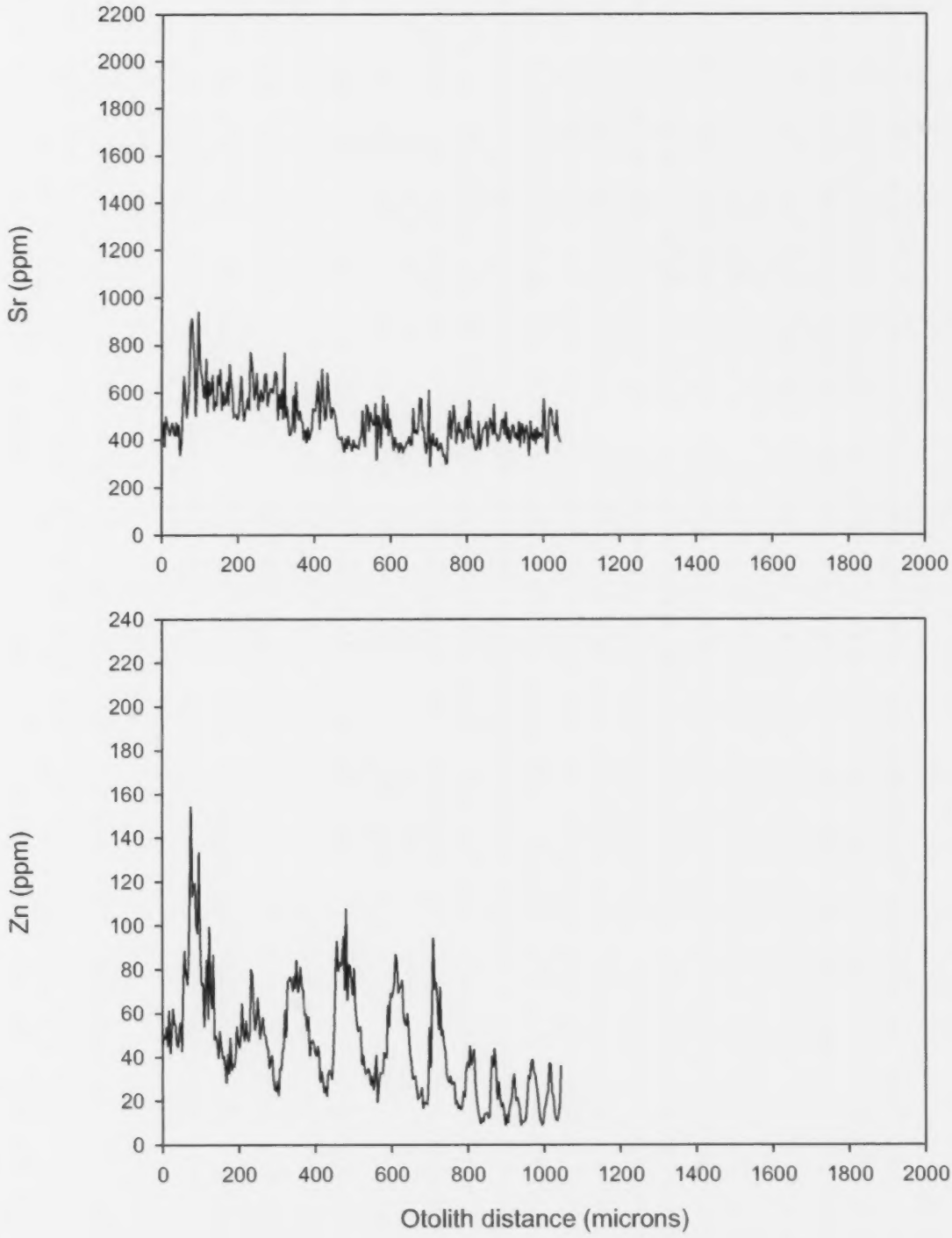

Figure 22. Strontium (top) and zinc (bottom) profiles from an LA-ICP-MS line-scan of an otolith from an Arctic char (#38335, 373 mm, 480 g, female, 12 yr) caught in Lake Hazen, June 20, 1992.

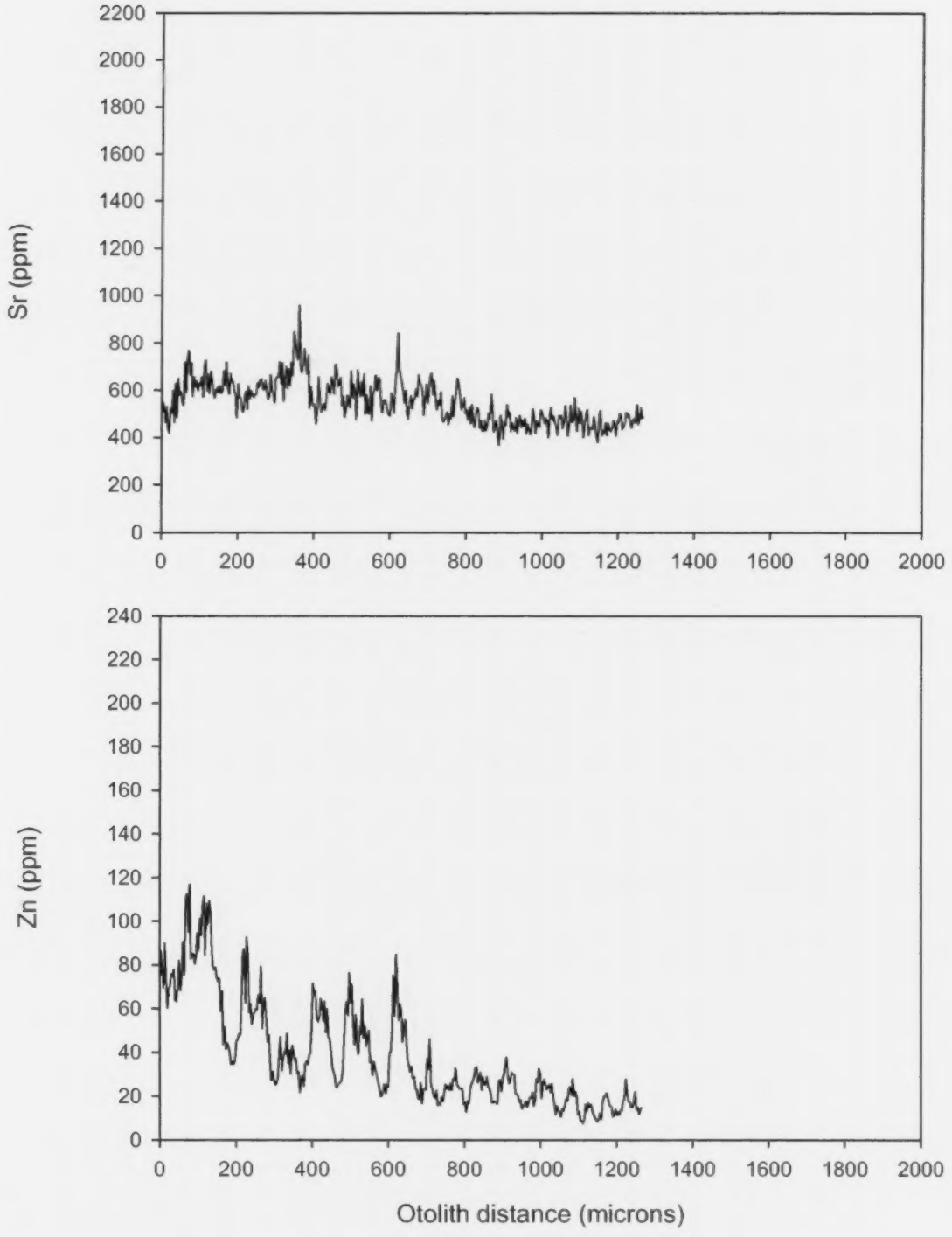

Figure 23. Strontium (top) and zinc (bottom) profiles from an LA-ICP-MS line-scan of an otolith from an Arctic char (#38336, 382 mm, 484 g, female, 16 yr) caught in Lake Hazen, June 20, 1992.

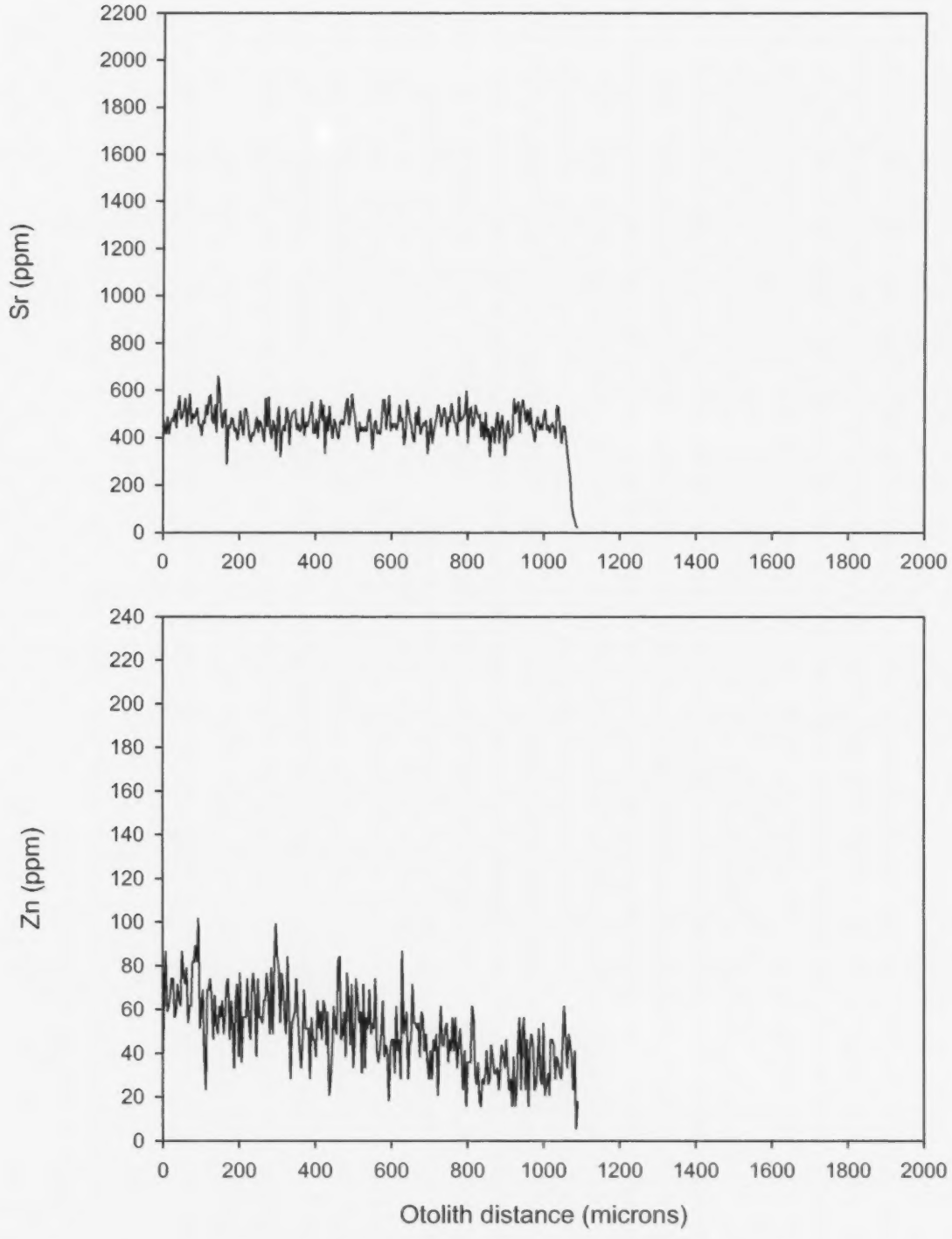

Figure 24. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47436, 249 mm, 140 g, female, 14 yr) caught in Lake Hazen, August 2, 2001.

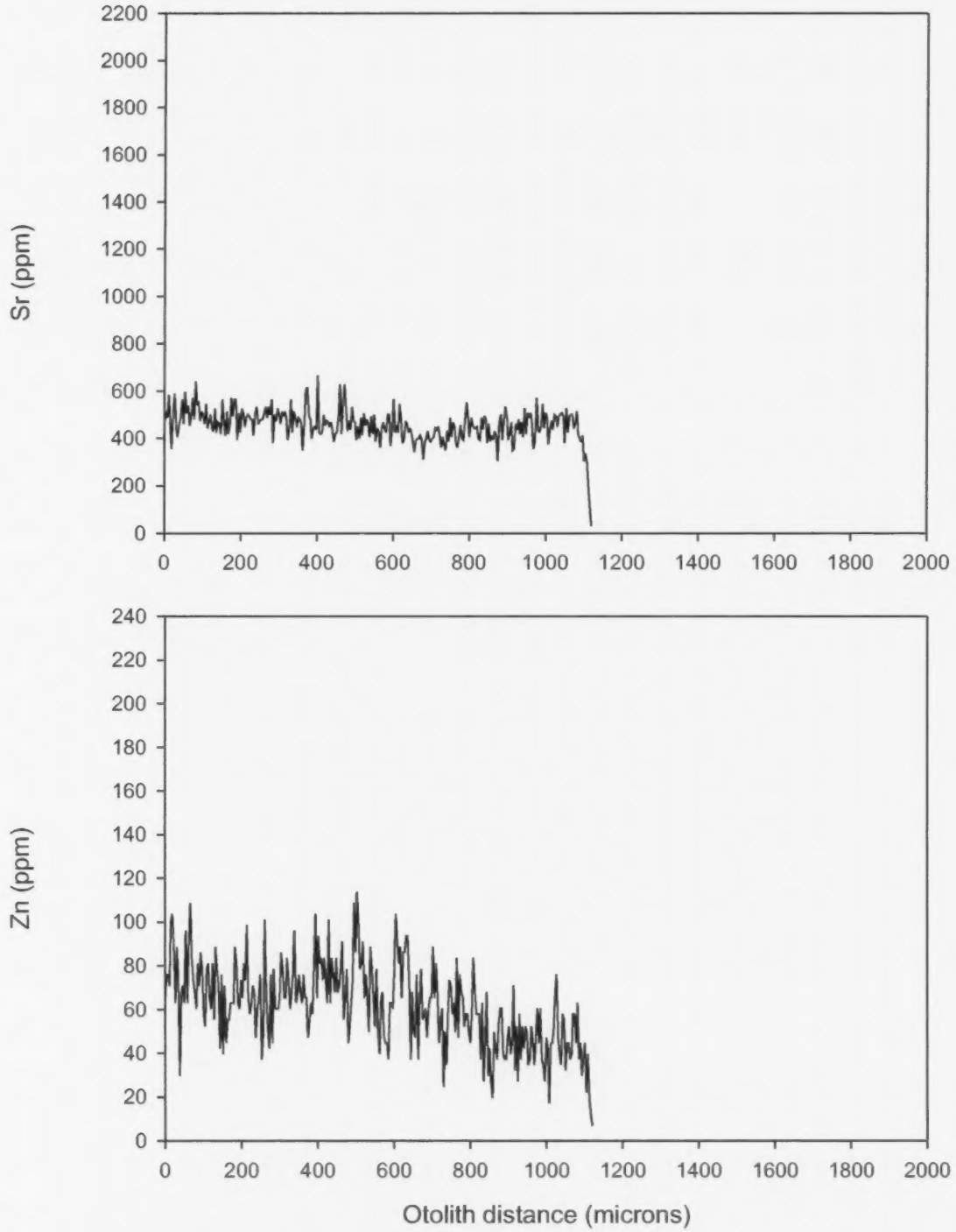

Figure 25. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47455, 204 mm, 77 g, male, 13 yr) caught in Lake Hazen, July 31, 2001.

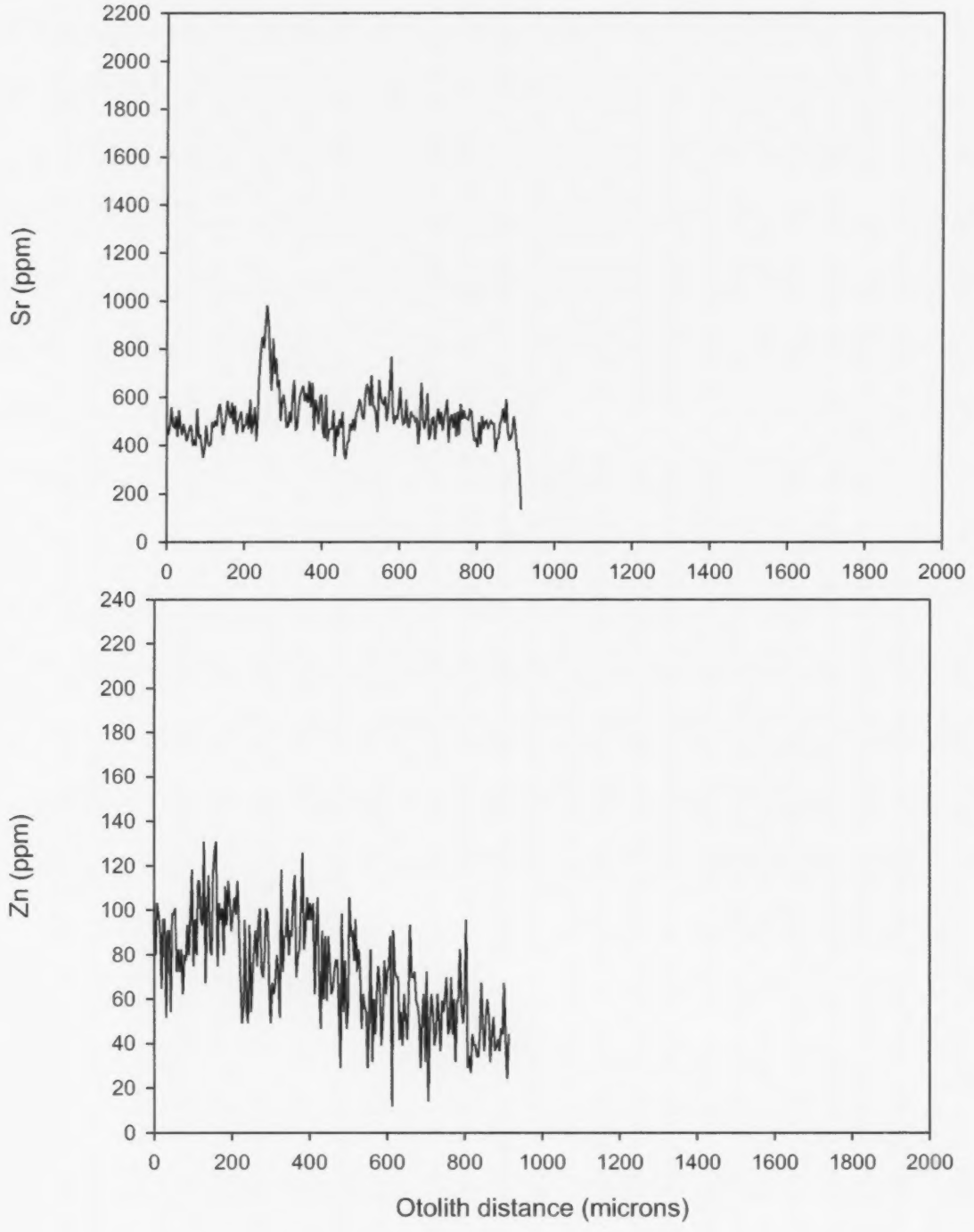

Figure 26. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47464, 162 mm, 49 g, male, 10 yr) caught in Lake Hazen, July 31, 2001.

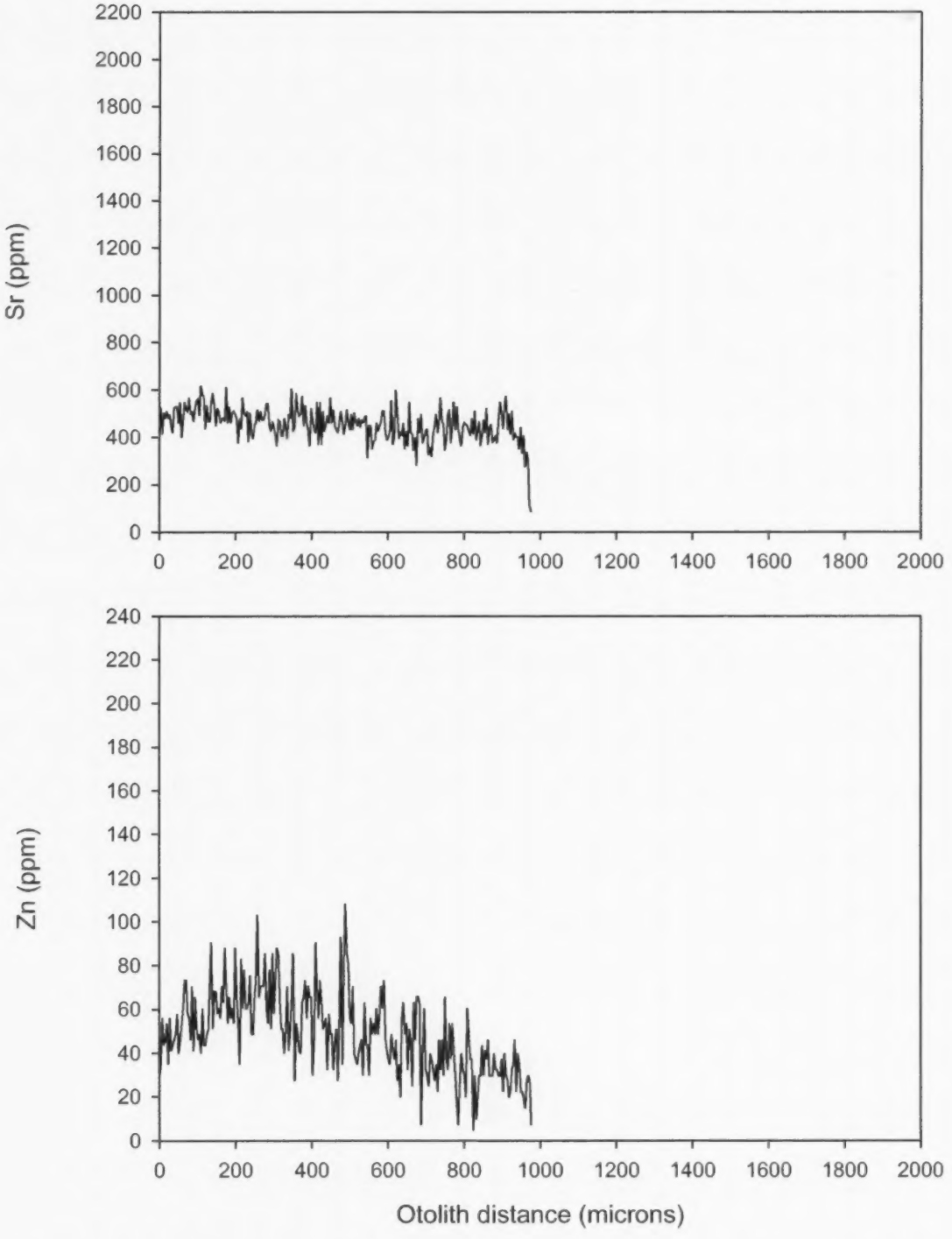

Figure 27. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47465, 202 mm, 78 g, female, 10 yr) caught in Lake Hazen, August 1, 2001.

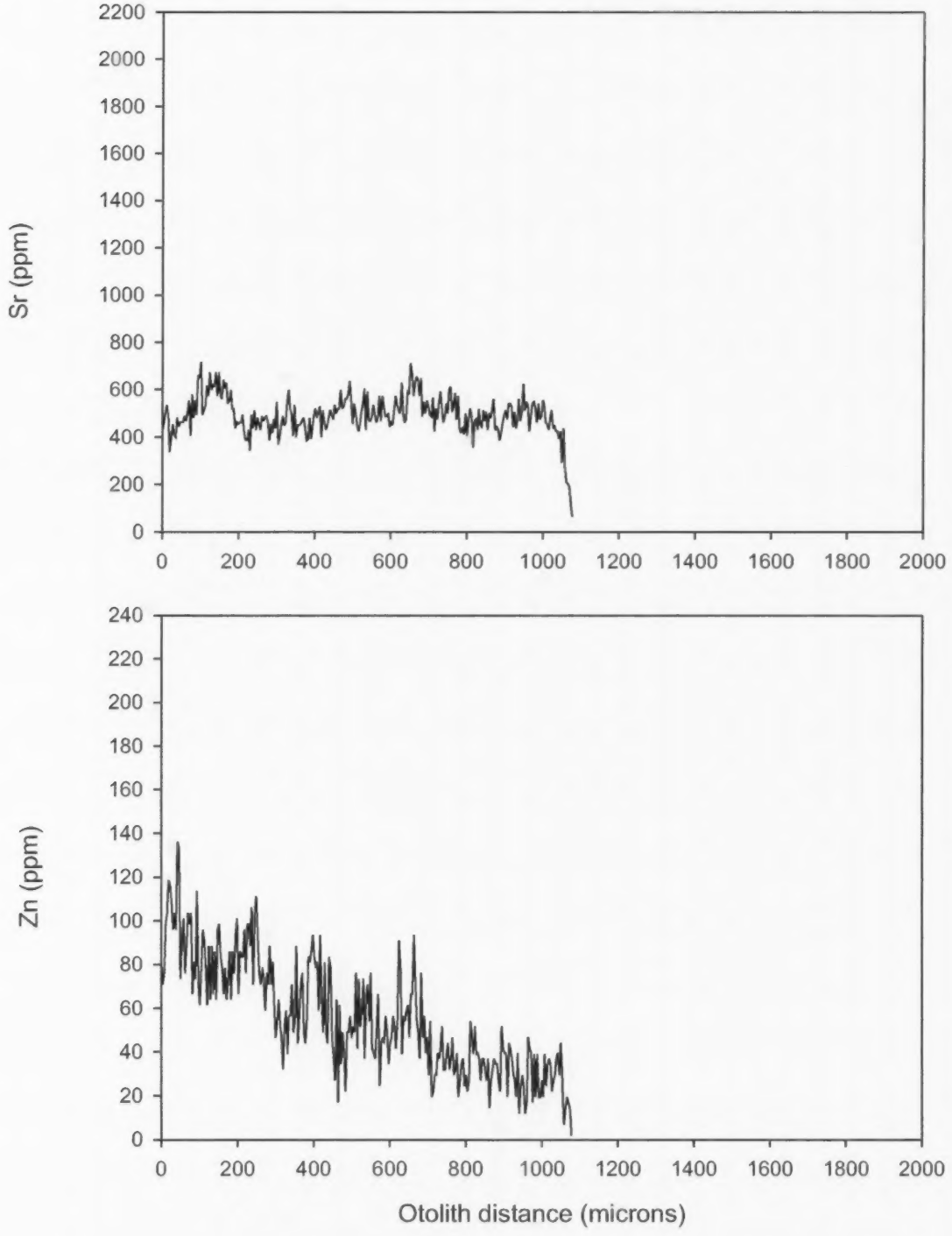

Figure 28. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47477, 178 mm, 48 g, male, 12 yr) caught in Lake Hazen, August 1, 2001.

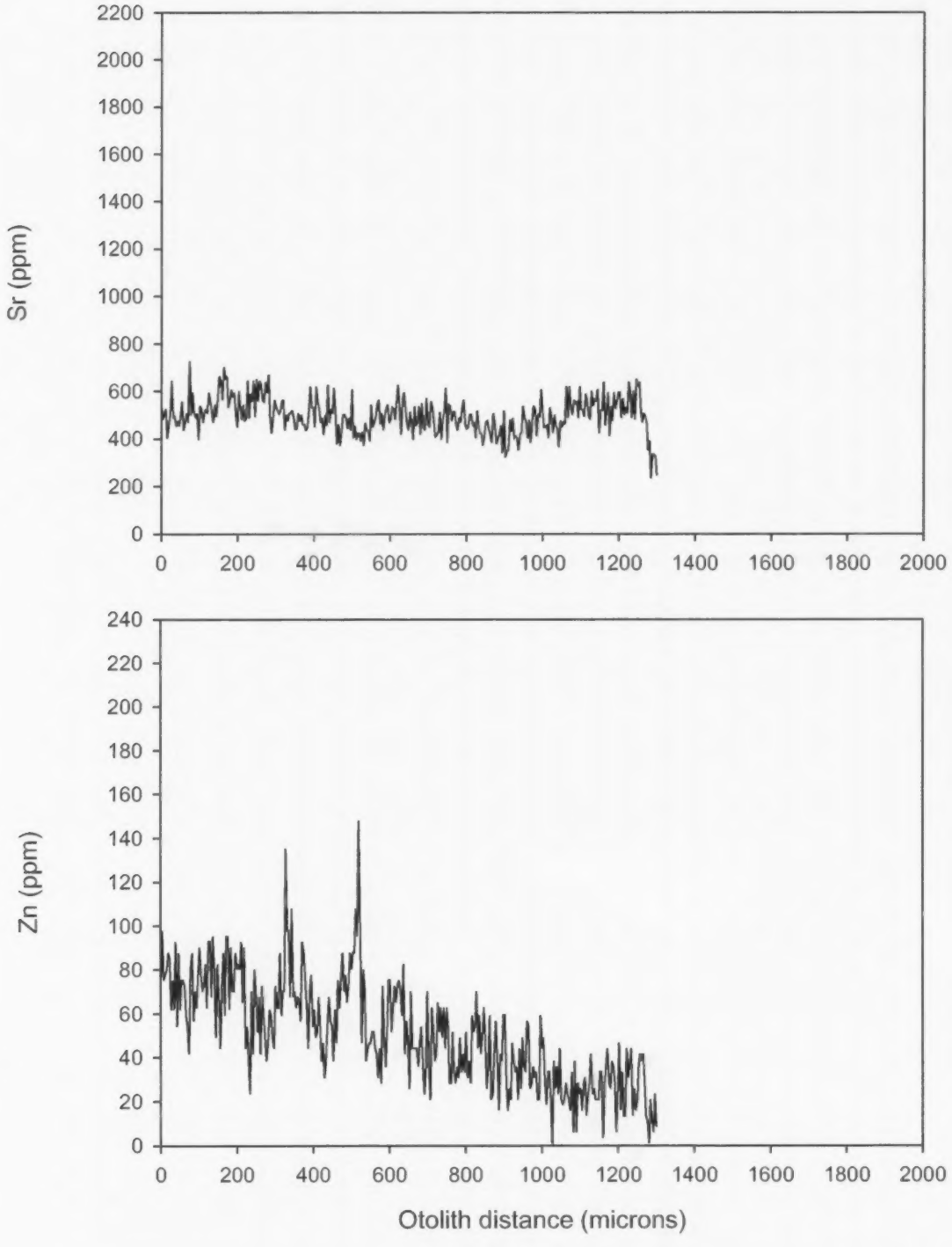

Figure 29. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47480, 207 mm, 74 g, female, 18 yr) caught in Lake Hazen, August 2, 2001.

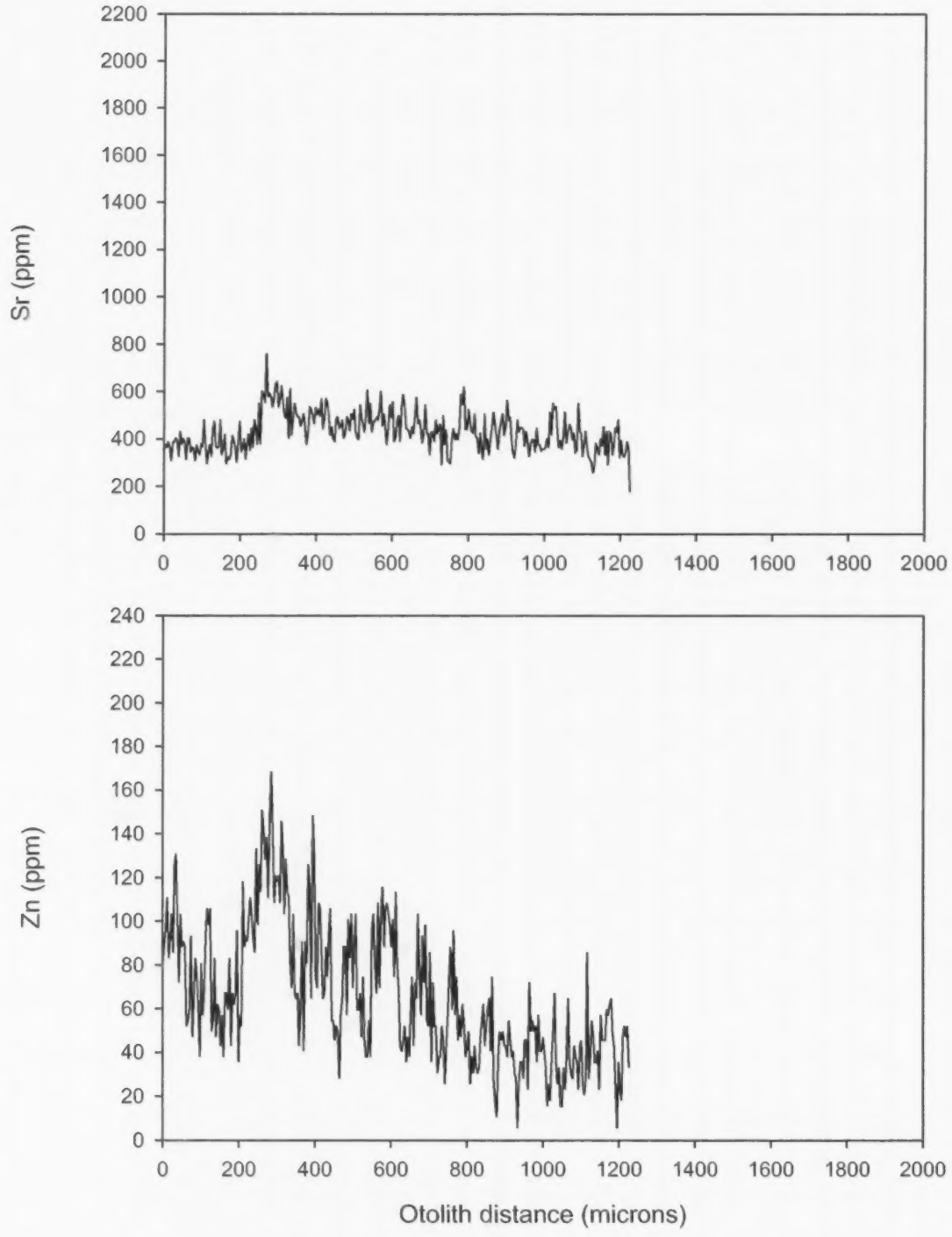

Figure 30. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47540, 240 mm, 140 g, female, 13 yr) caught in Lake Hazen, August 2, 2001.

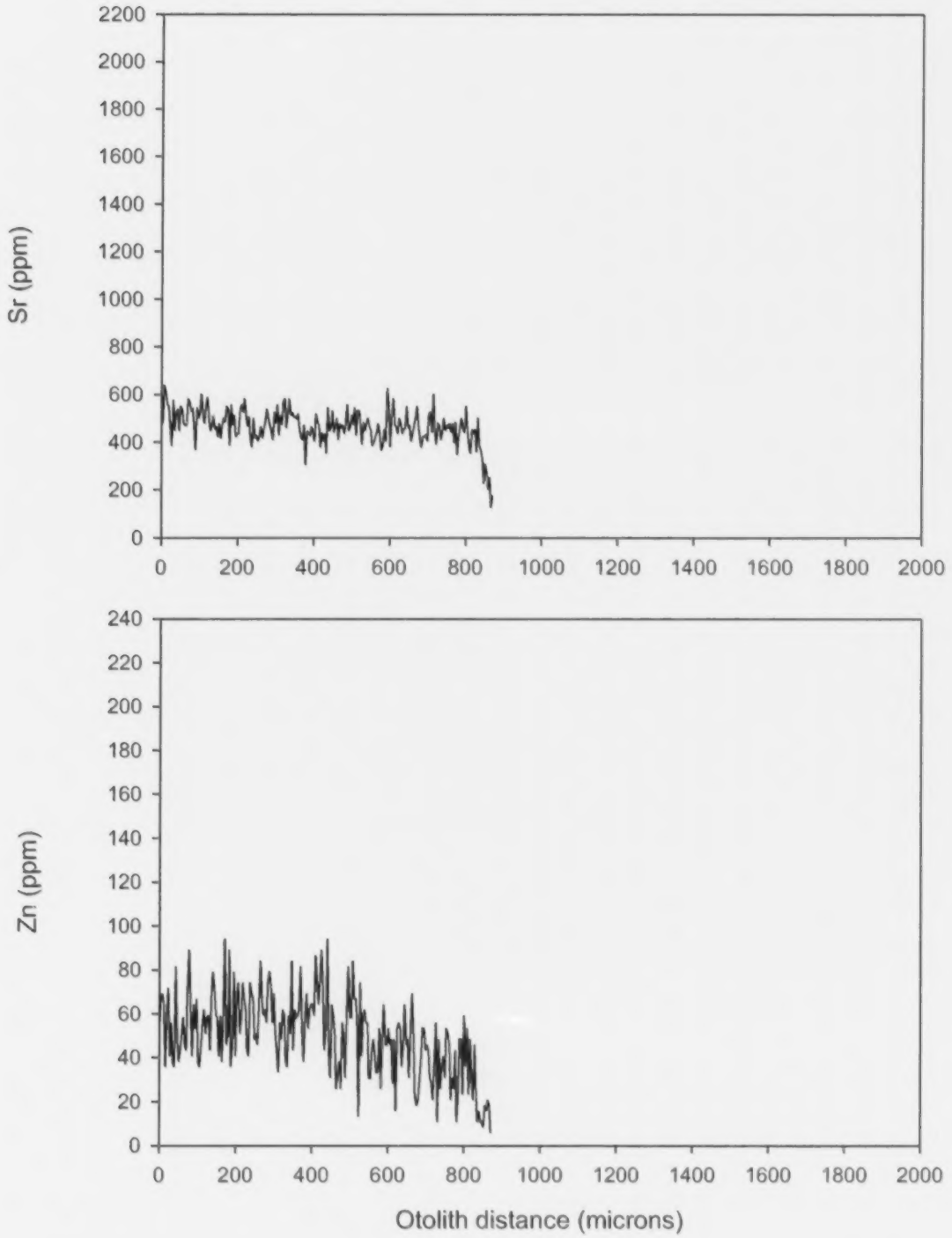

Figure 31. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47557, 201 mm, 74 g, male, 8 yr) caught in Lake Hazen, July 31, 2001.

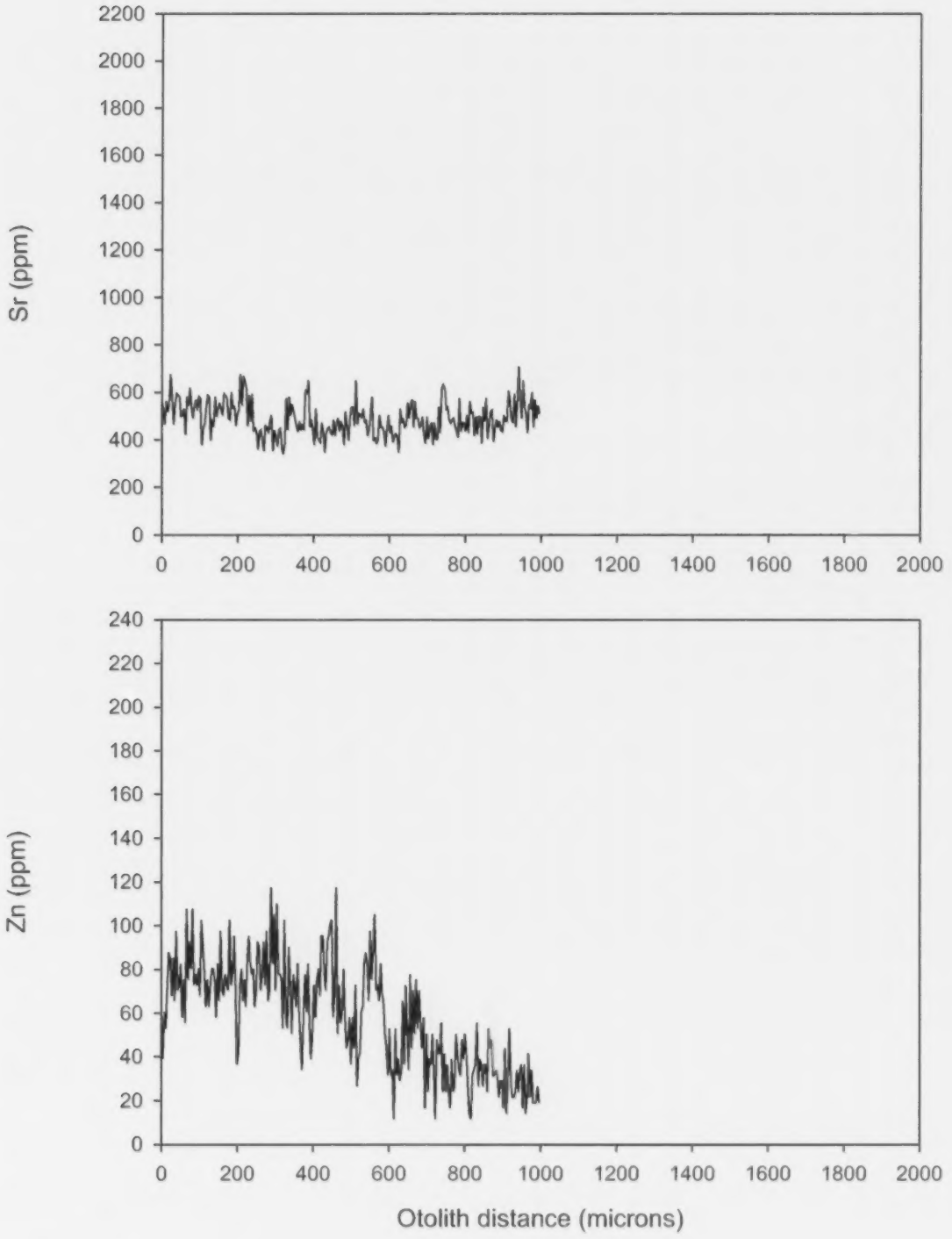

Figure 32. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#HA183, 158 mm, no weight taken, male, 10 yr) caught in Lake Hazen, August 13, 2001.

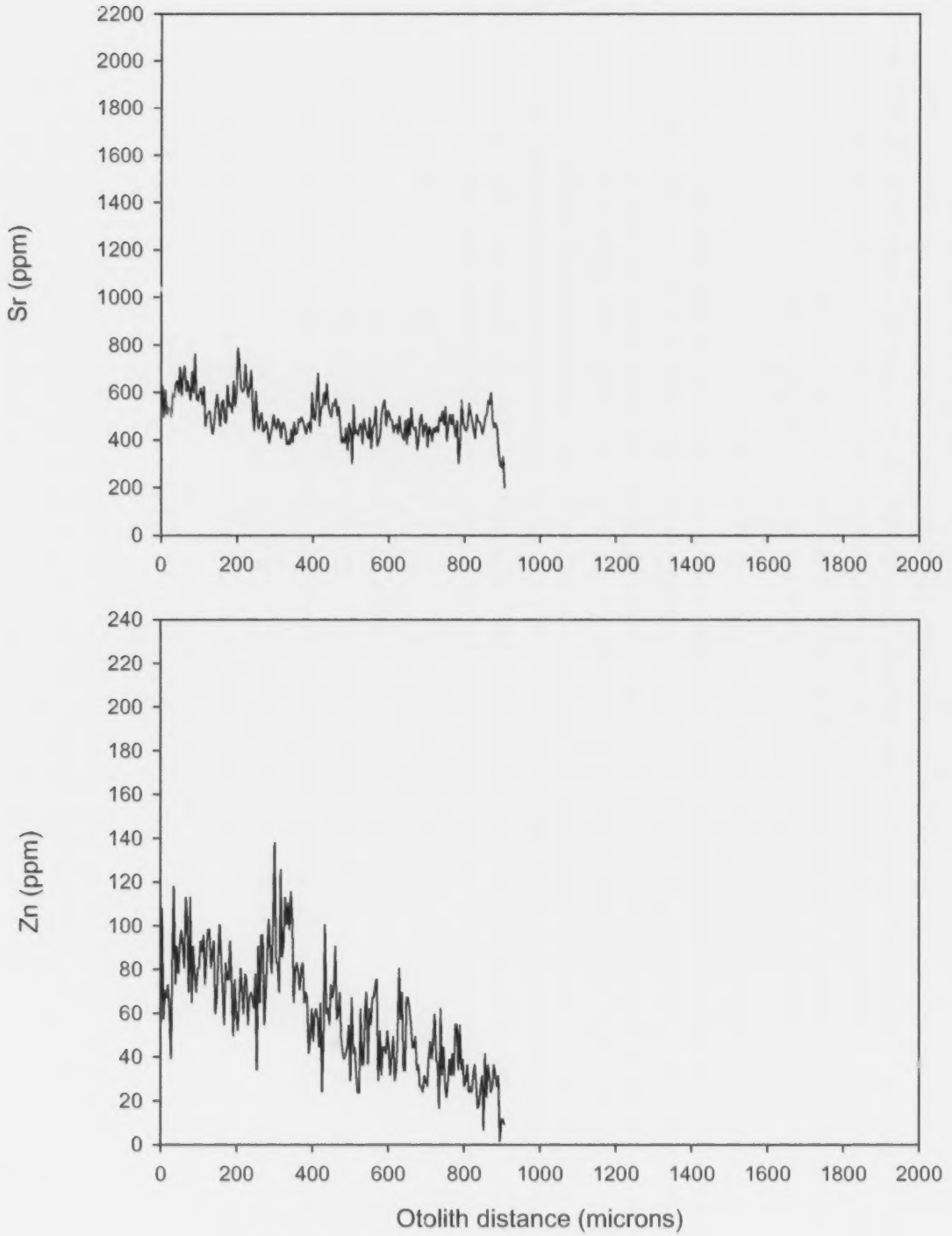

Figure 33. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#HA184, 167 mm, no weight taken, female, 10 yr) caught in Lake Hazen, August 13, 2001.

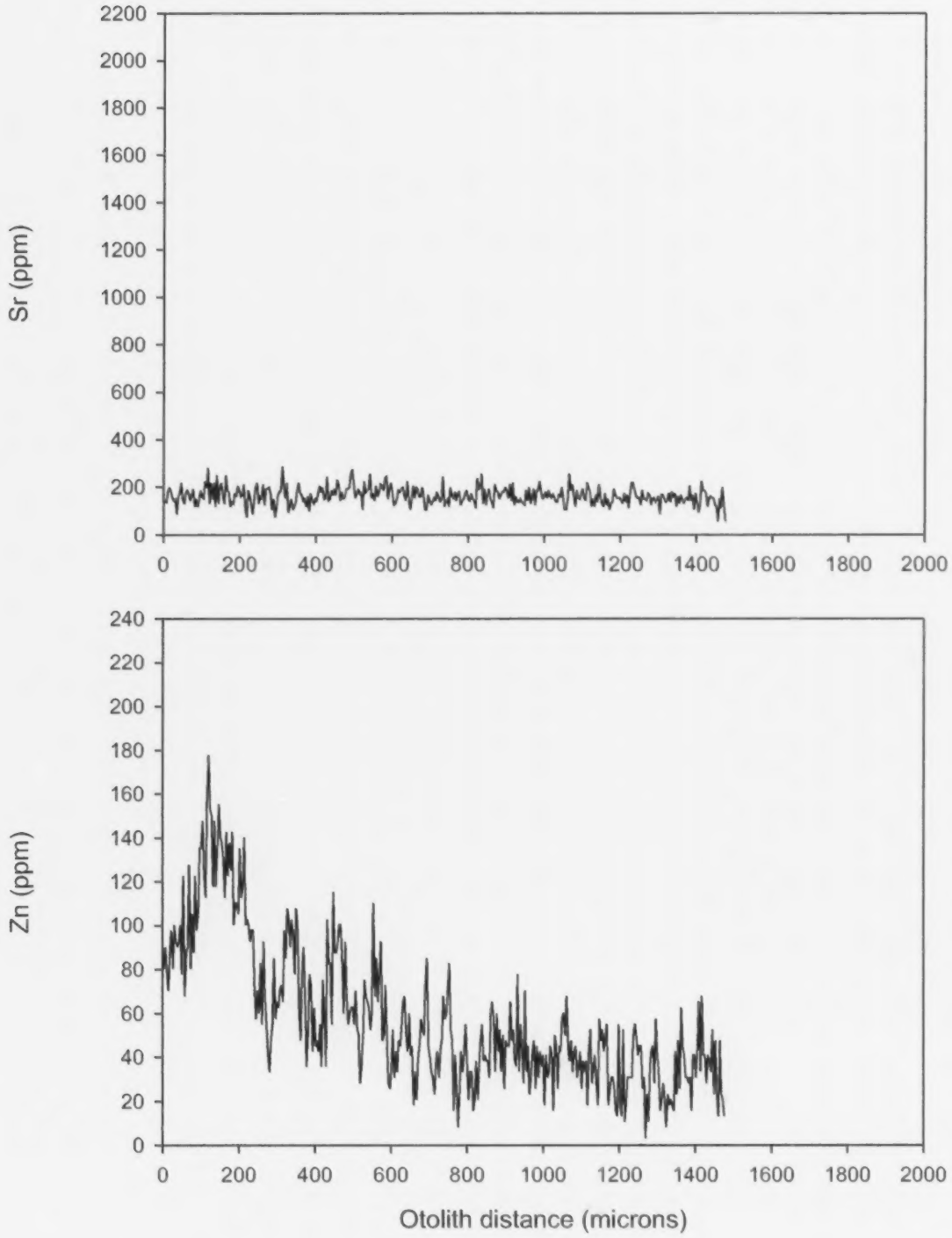

Figure 34. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47371, 430 mm, 740 g, male, 19 yr) caught in Lower Beaufort Lake, August 9, 2001.

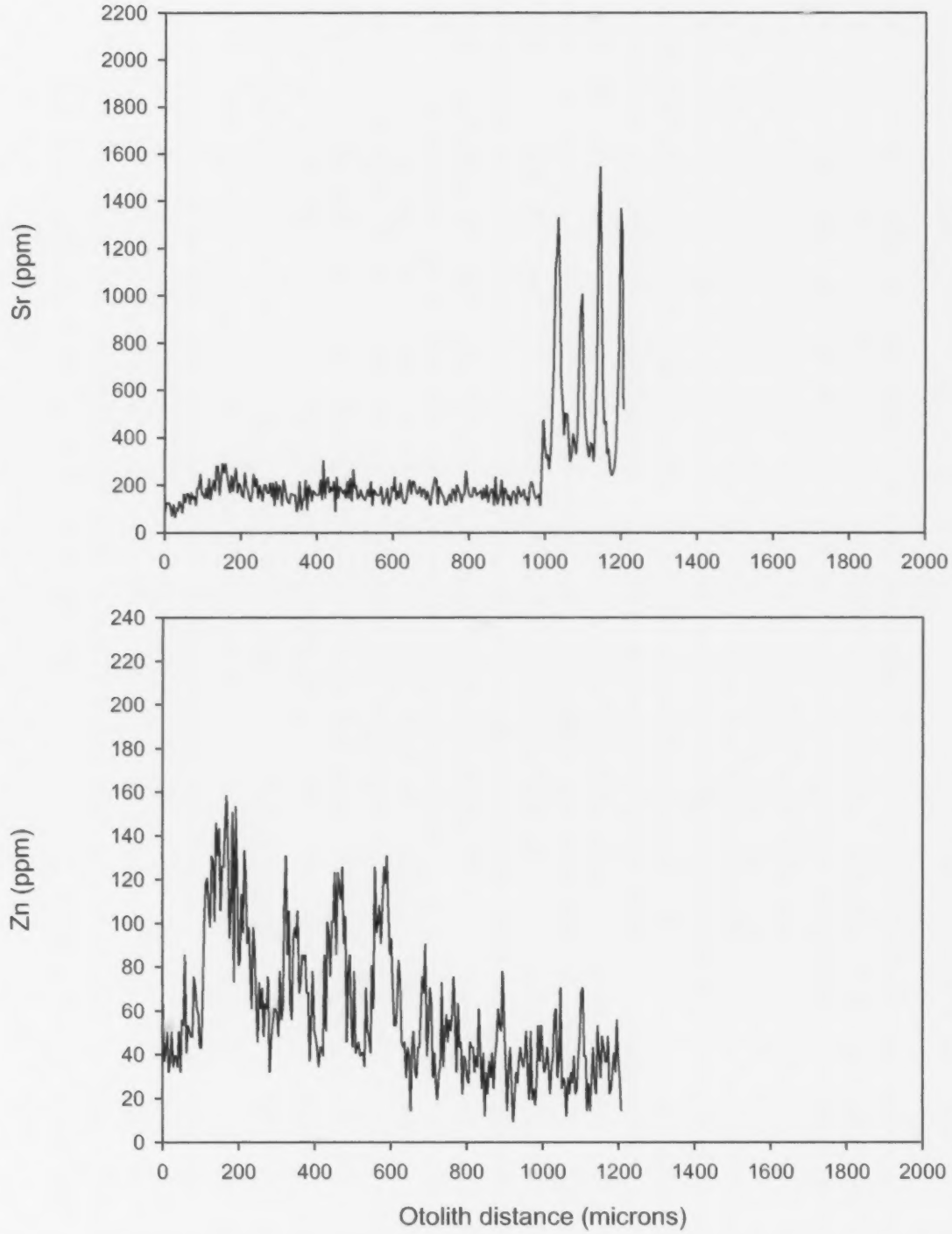

Figure 35. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47373, 366 mm, 440 g, female, 13 yr) caught in Lower Beaufort Lake, August 9, 2001.

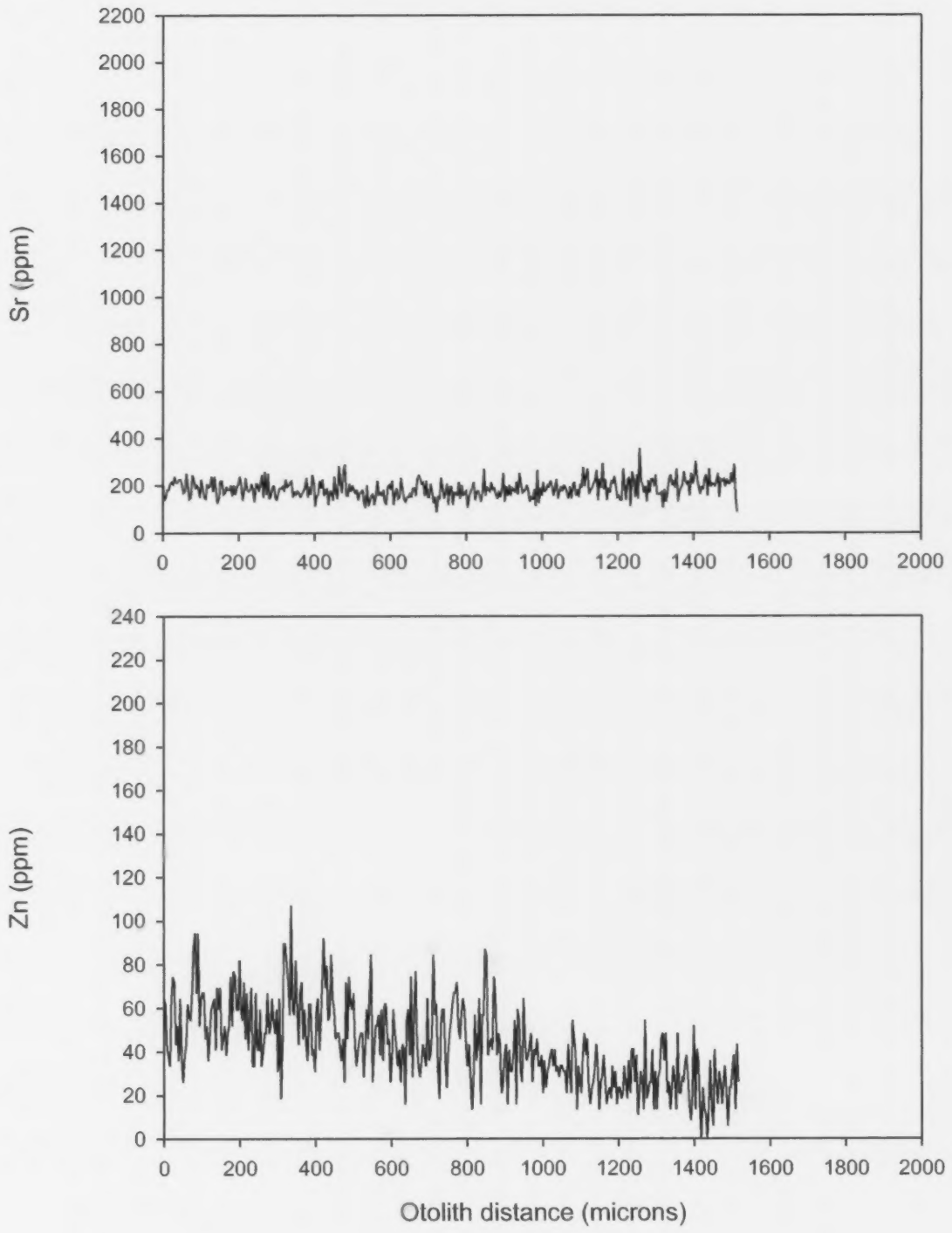

Figure 36. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47374, 327 mm, 320 g, male, 28 yr) caught in Lower Beaufort Lake, August 9, 2001.

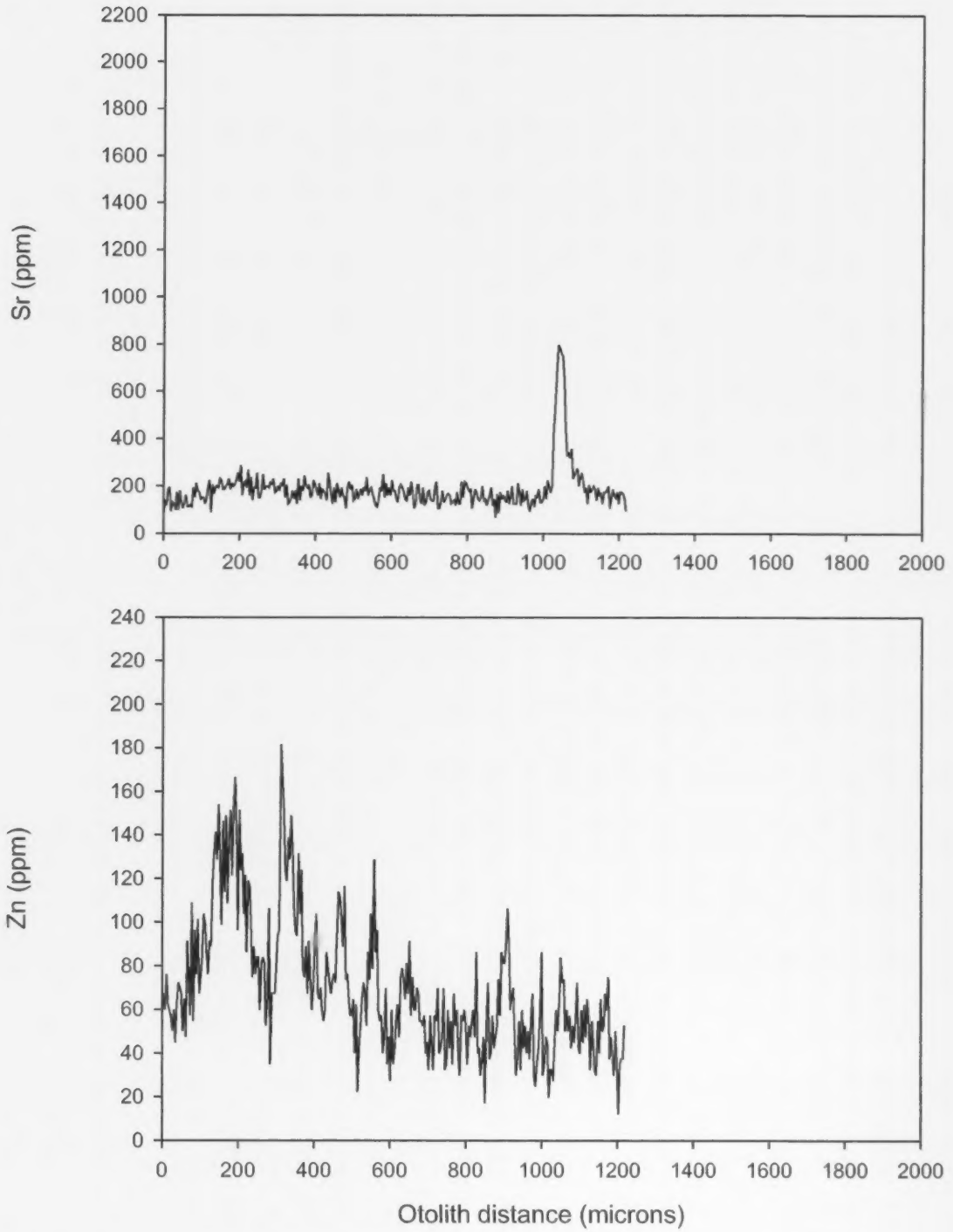

Figure 37. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47376, 325 mm, 340 g, female, 14 yr) caught in Lower Beaufort Lake, August 9, 2001.

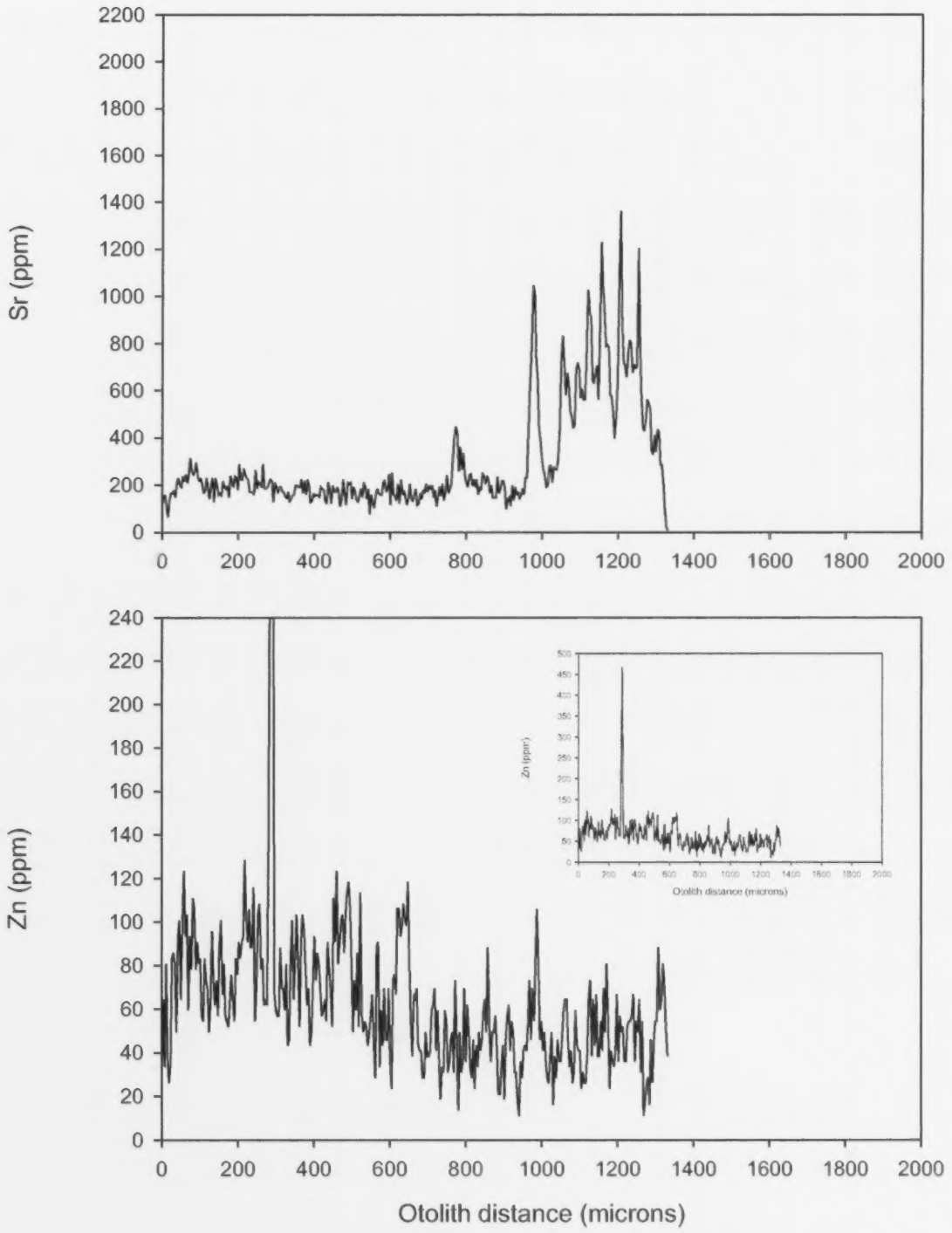

Figure 38. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47378, 392 mm, 510 g, female, 18 yr) caught in Lower Beaufort Lake, August 10, 2001.

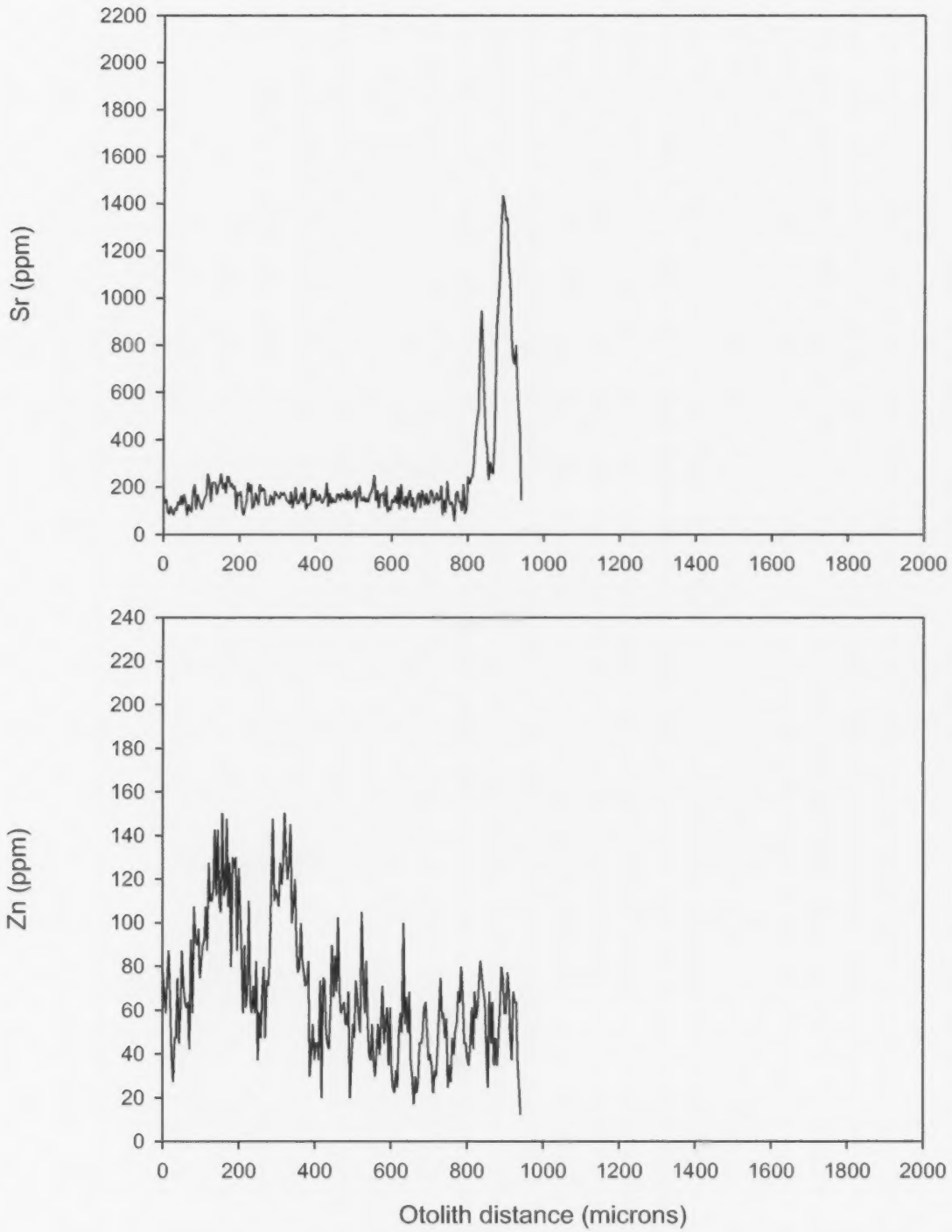

Figure 39. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47380, 261 mm, 150 g, male, 12 yr) caught in Lower Beaufort Lake, August 9, 2001.

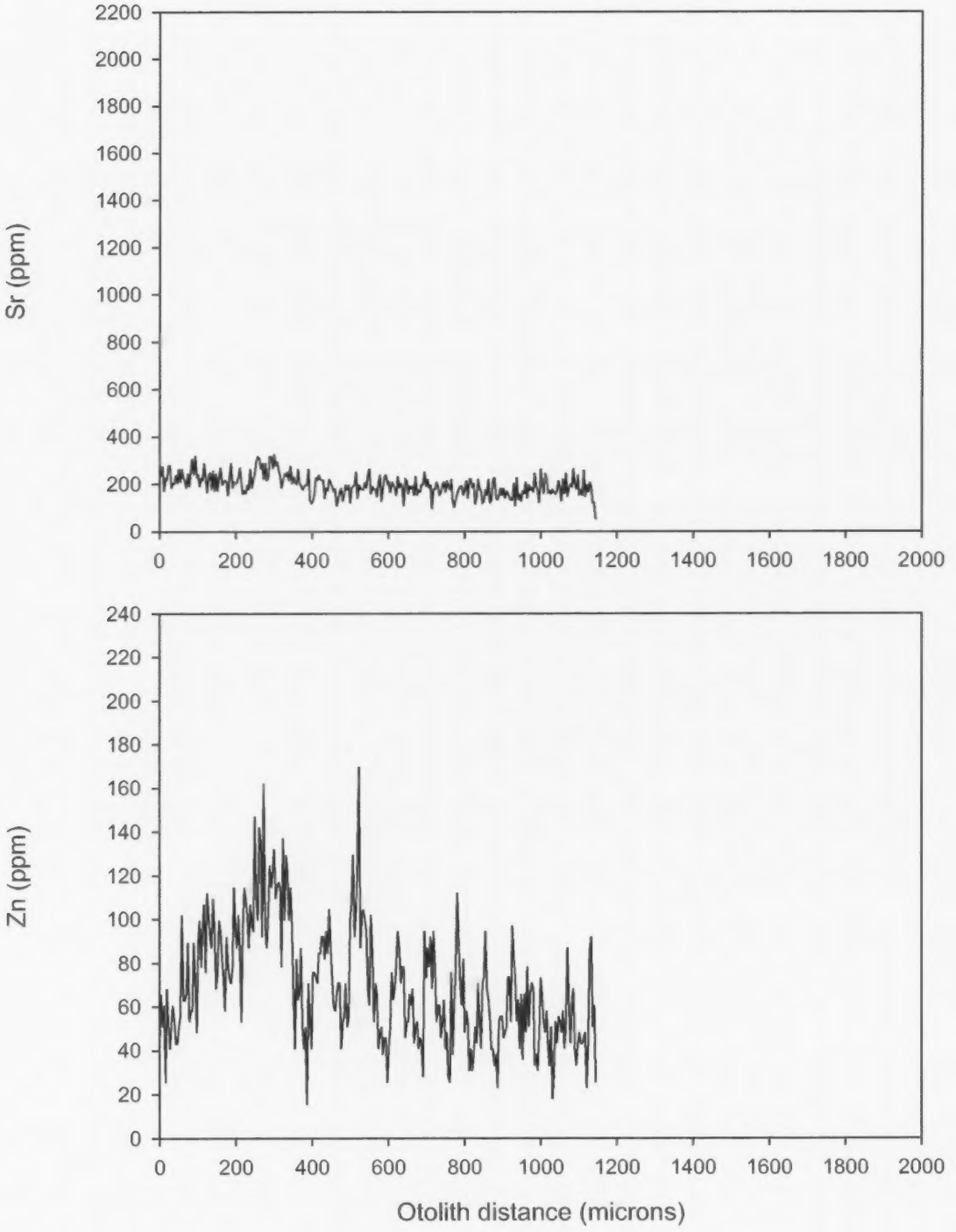

Figure 40. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47381, 243 mm, 120 g, female, 10 yr) caught in Lower Beaufort Lake, August 10, 2001.

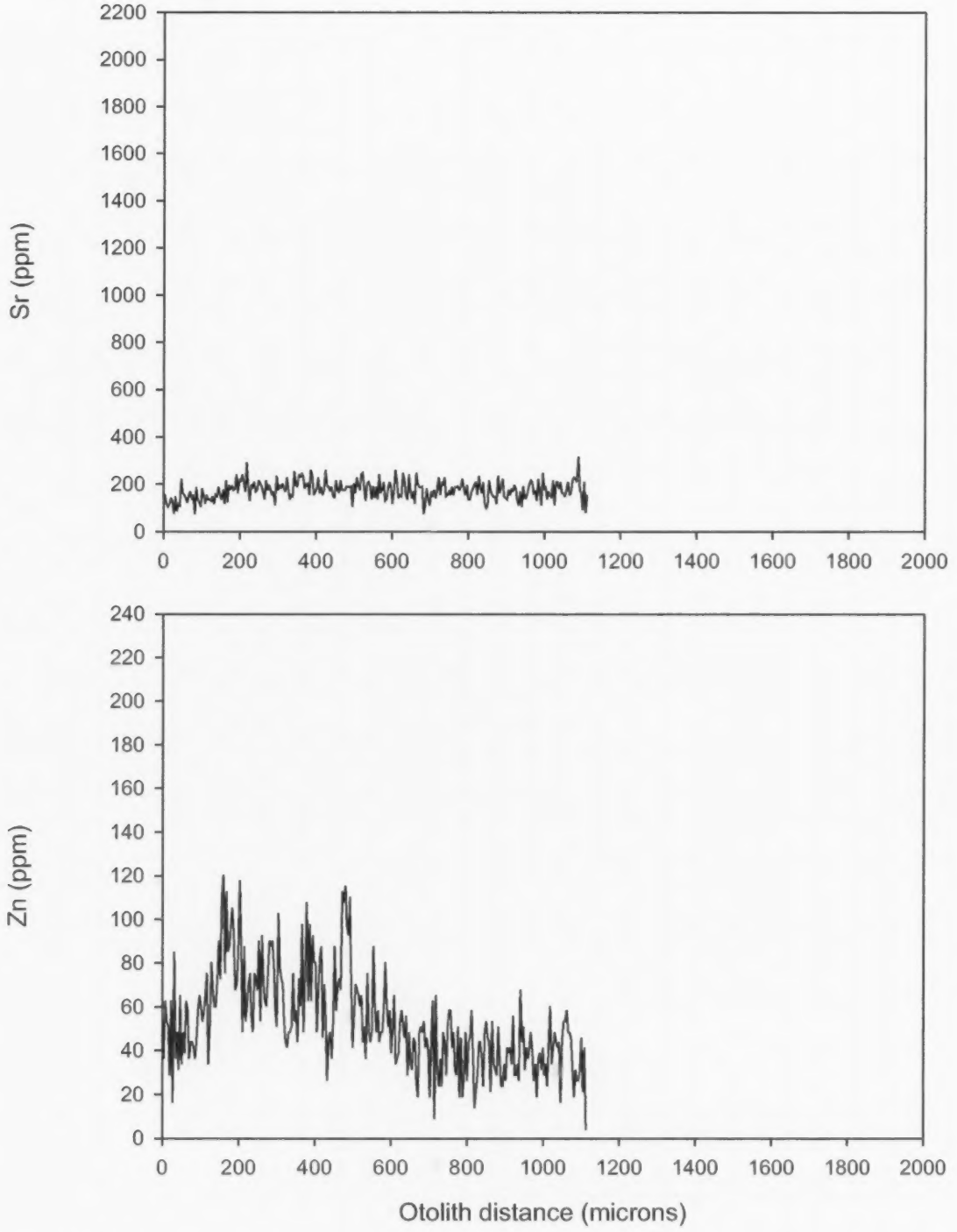

Figure 41. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47382, 257 mm, 150 g, female, 14 yr) caught in Lower Beaufort Lake, August 10, 2001.

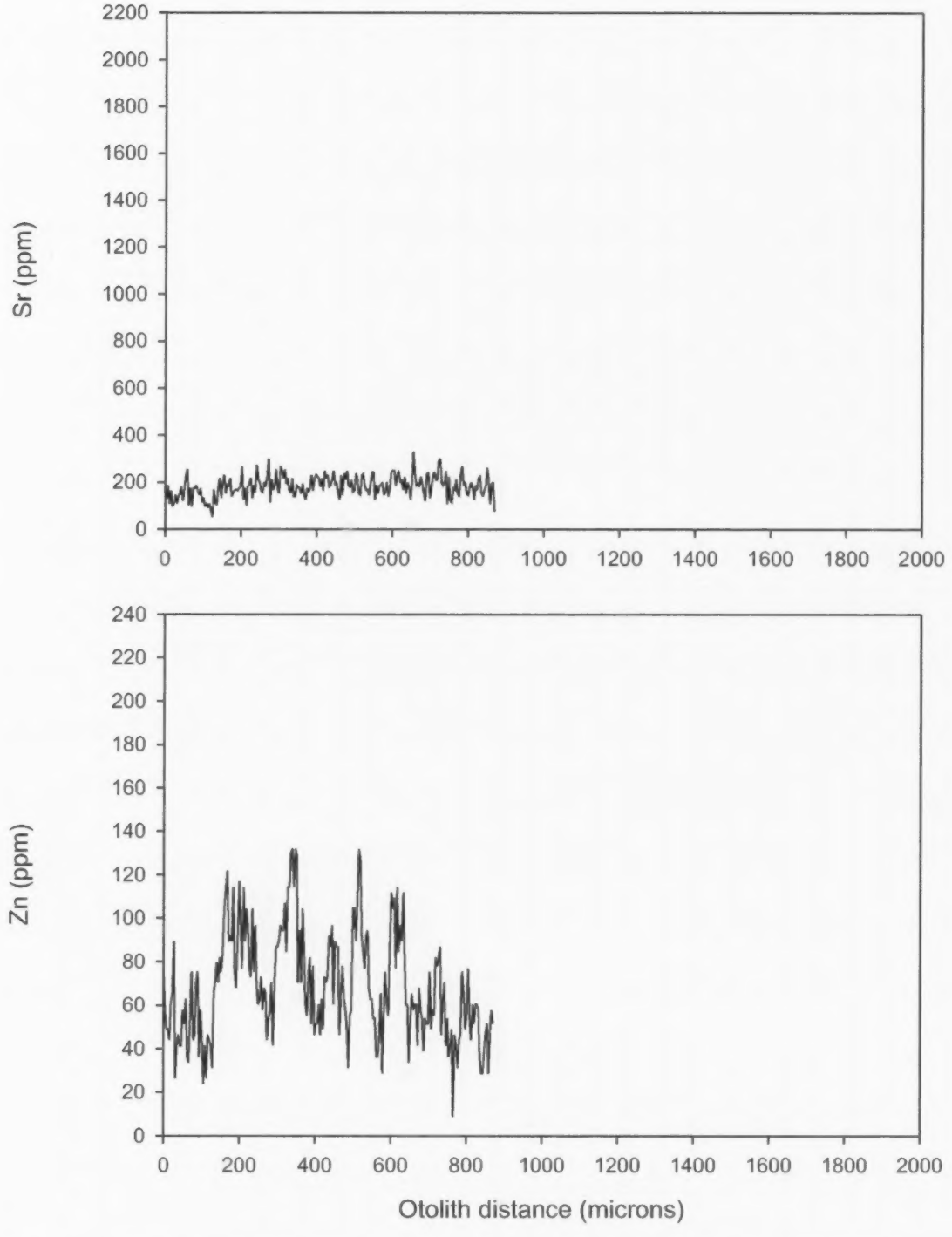

Figure 42. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47388, 147 mm, 30 g, female, 7 yr) caught in Lower Beaufort Lake, August 9, 2001.

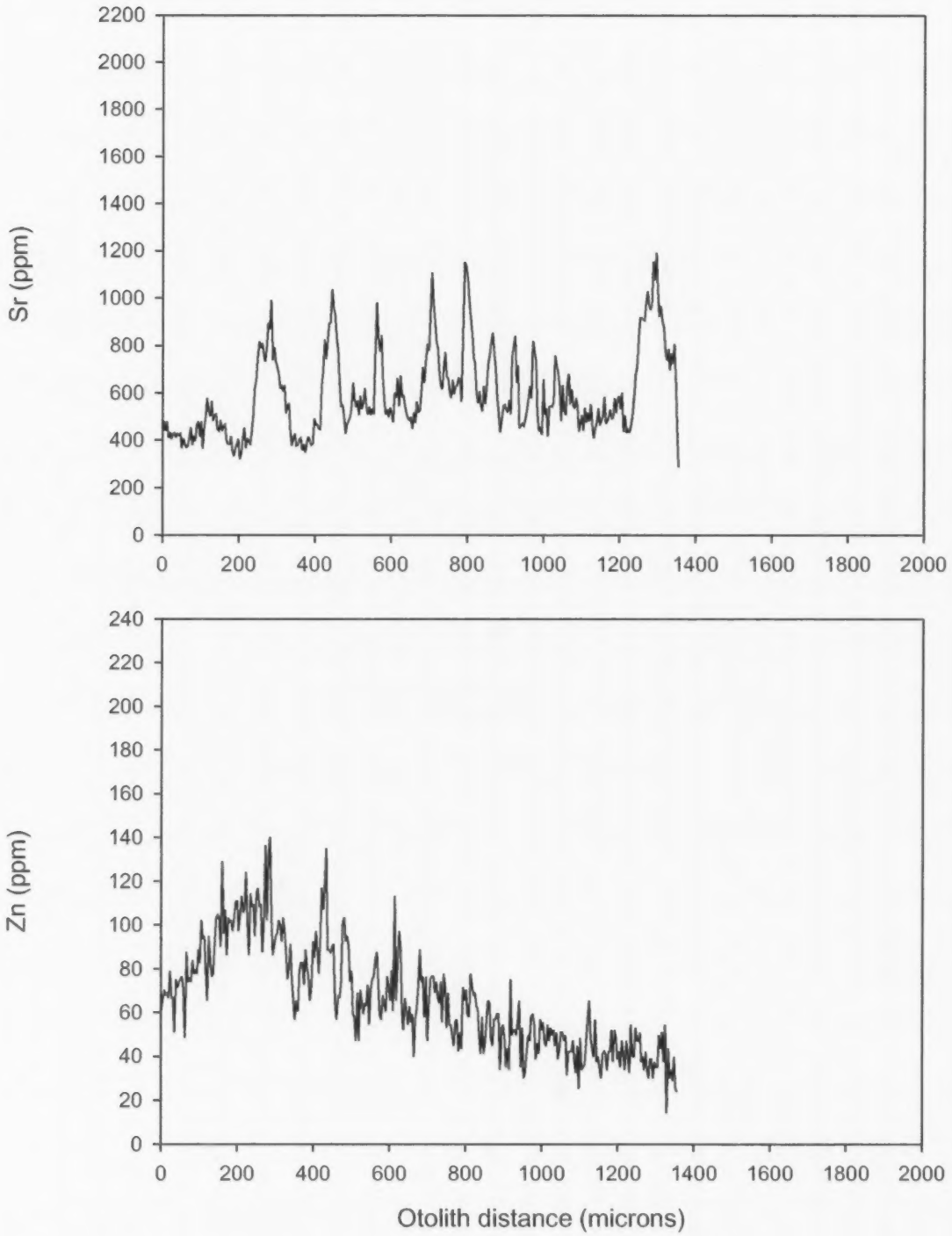

Figure 43. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#49047, 356 mm, 526 g, male, 15 yr) caught in Rambow Hill Lake, July 27-28, 2002.

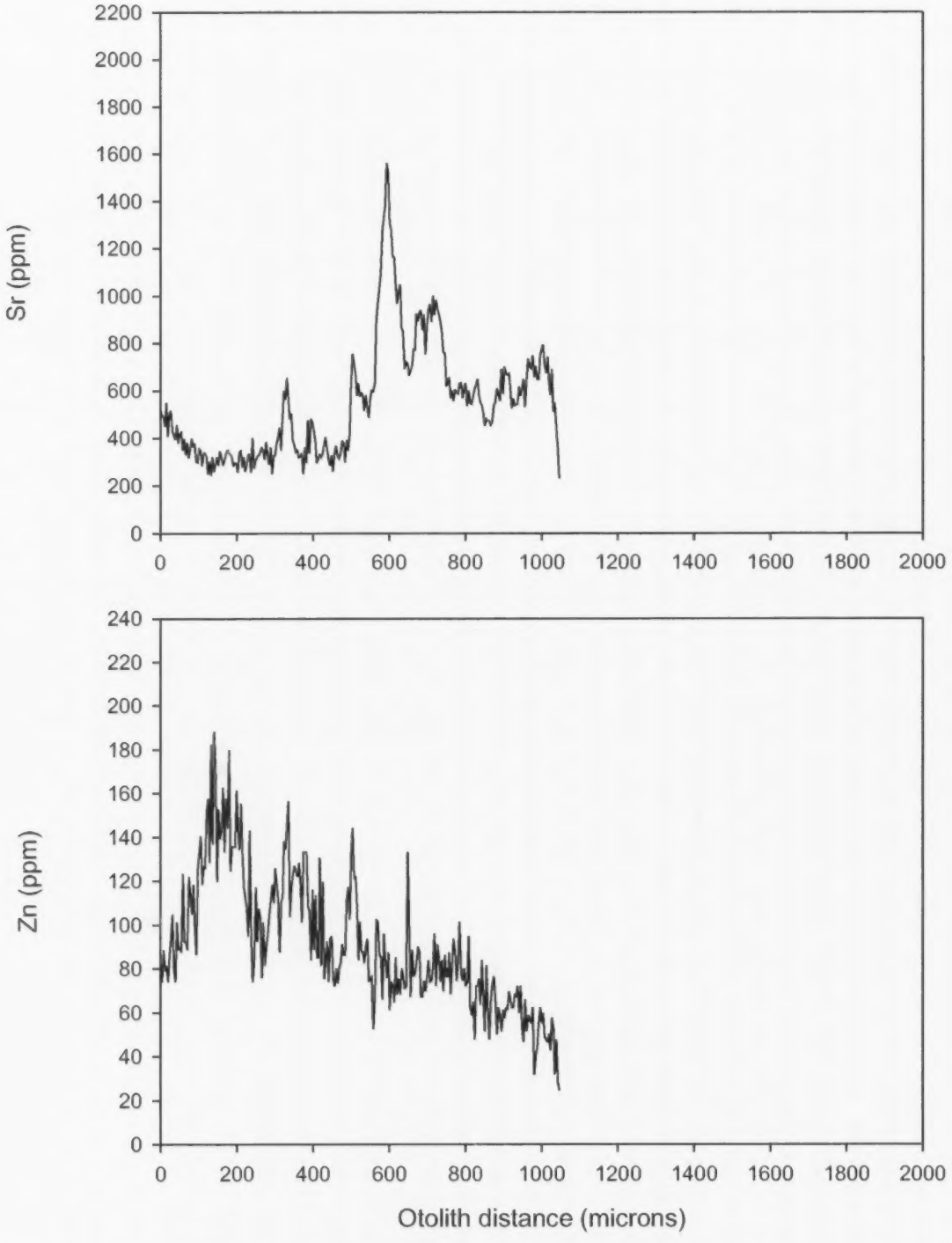

Figure 44. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#49049, 303 mm, 296 g, female, 10 yr) caught in Rambow Hill Lake, July 27-28, 2002.

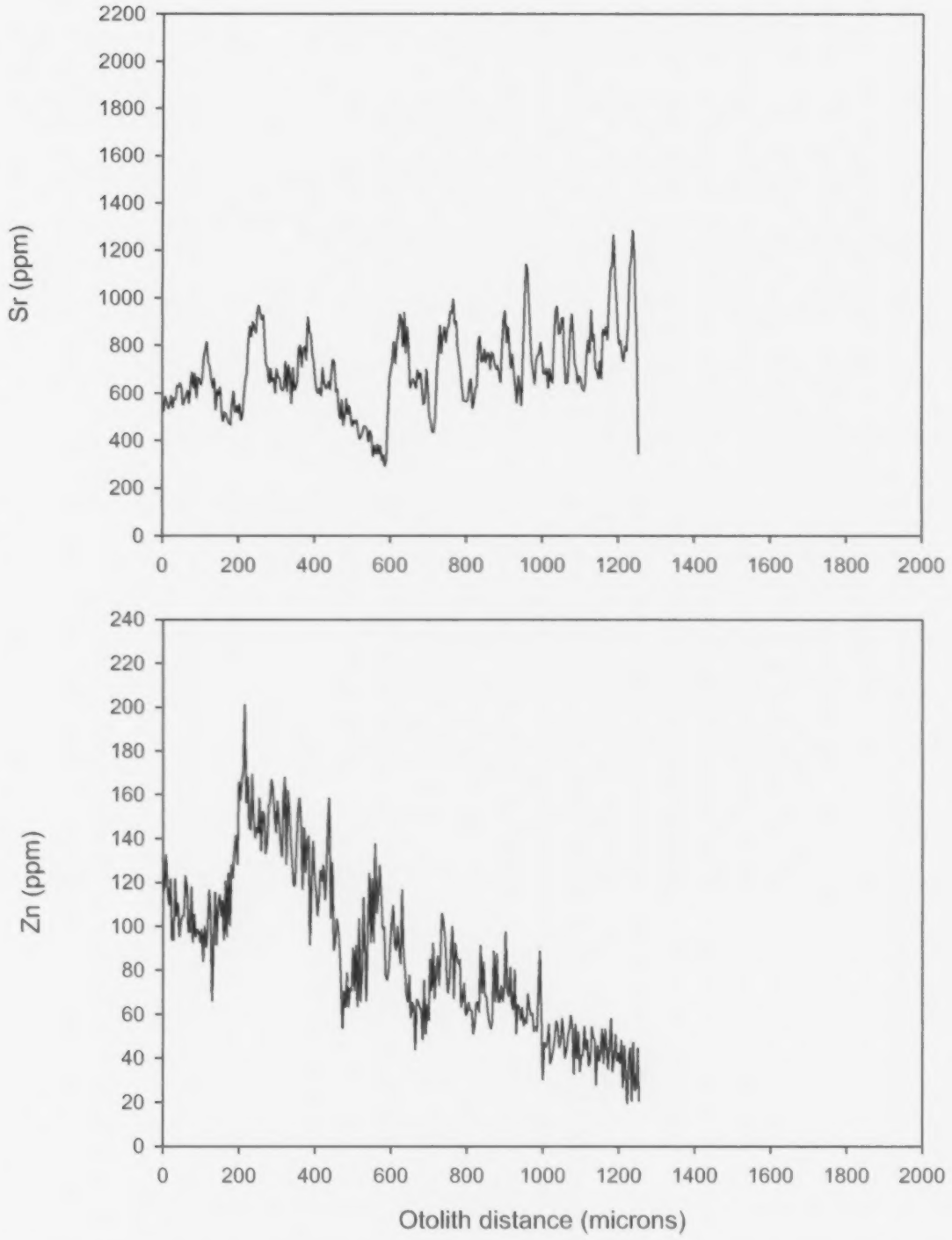

Figure 45. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#49050, 286 mm, 211 g, female, 12 yr) caught in Rambow Hill Lake, July 27-28, 2002.

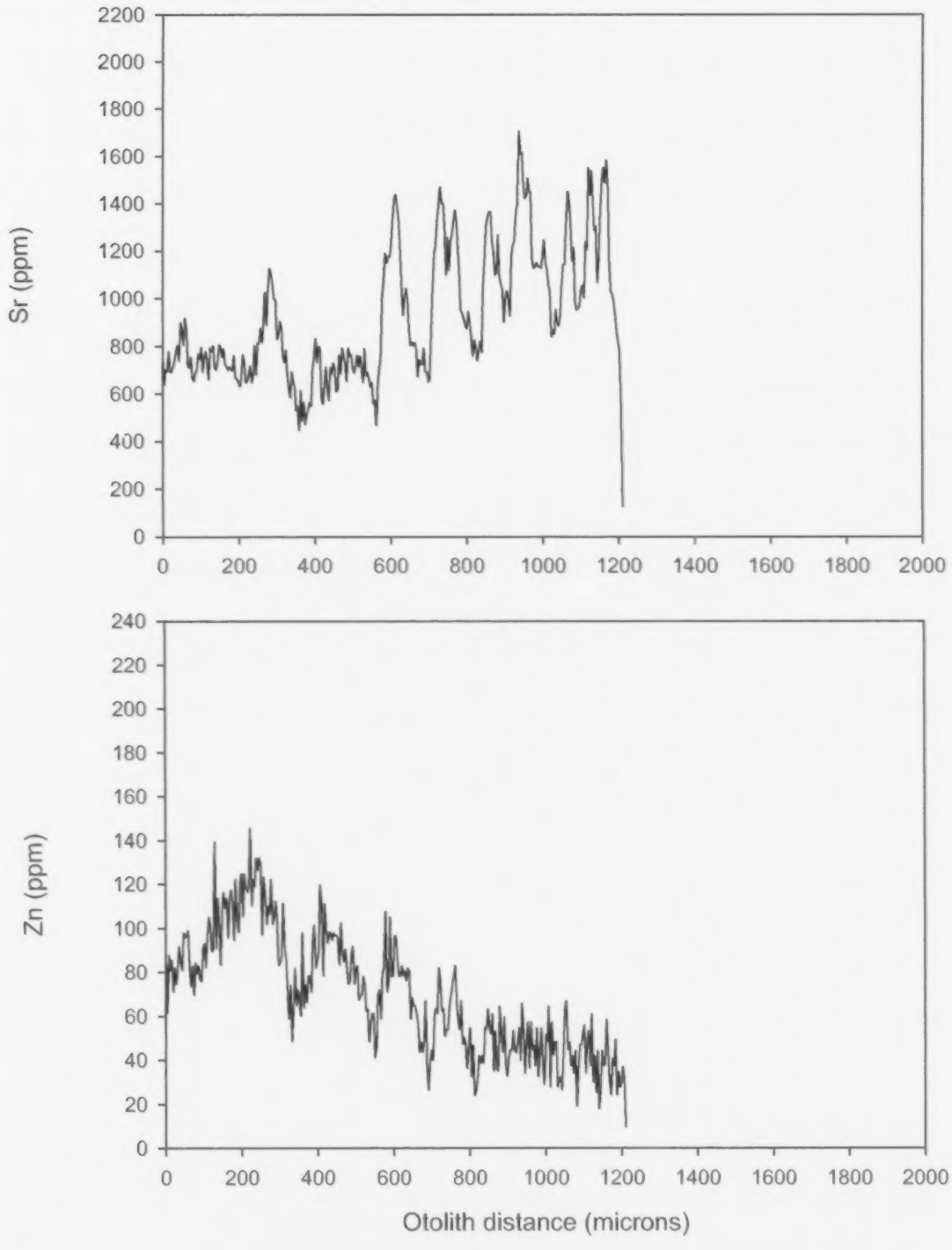

Figure 46. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#49054, 260 mm, 187 g, female, 10 yr) caught in Rambow Hill Lake, July 27-28, 2002.

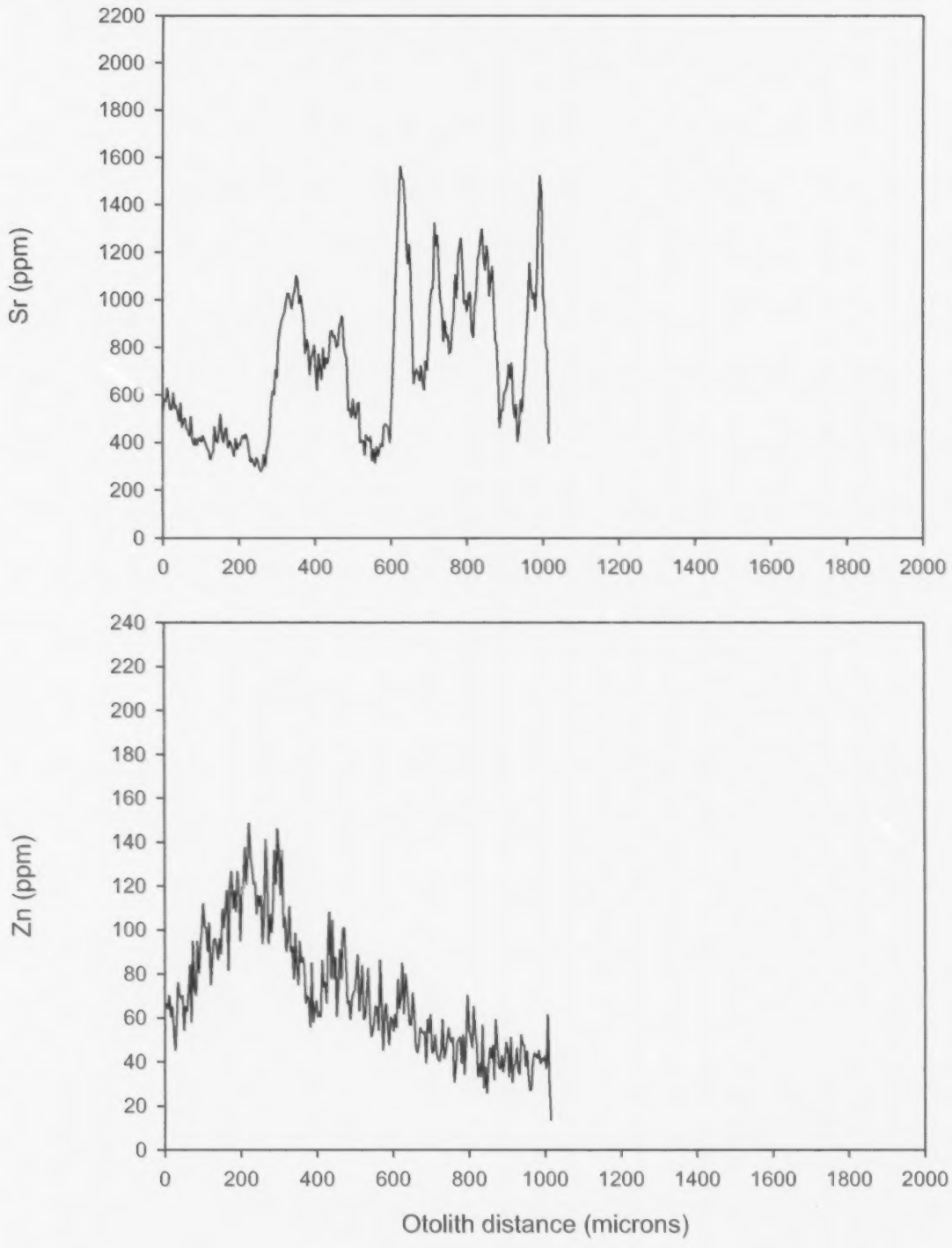

Figure 47. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#49055, 276 mm, 199 g, male, 11 yr) caught in Rambow Hill Lake, July 27-28, 2002.

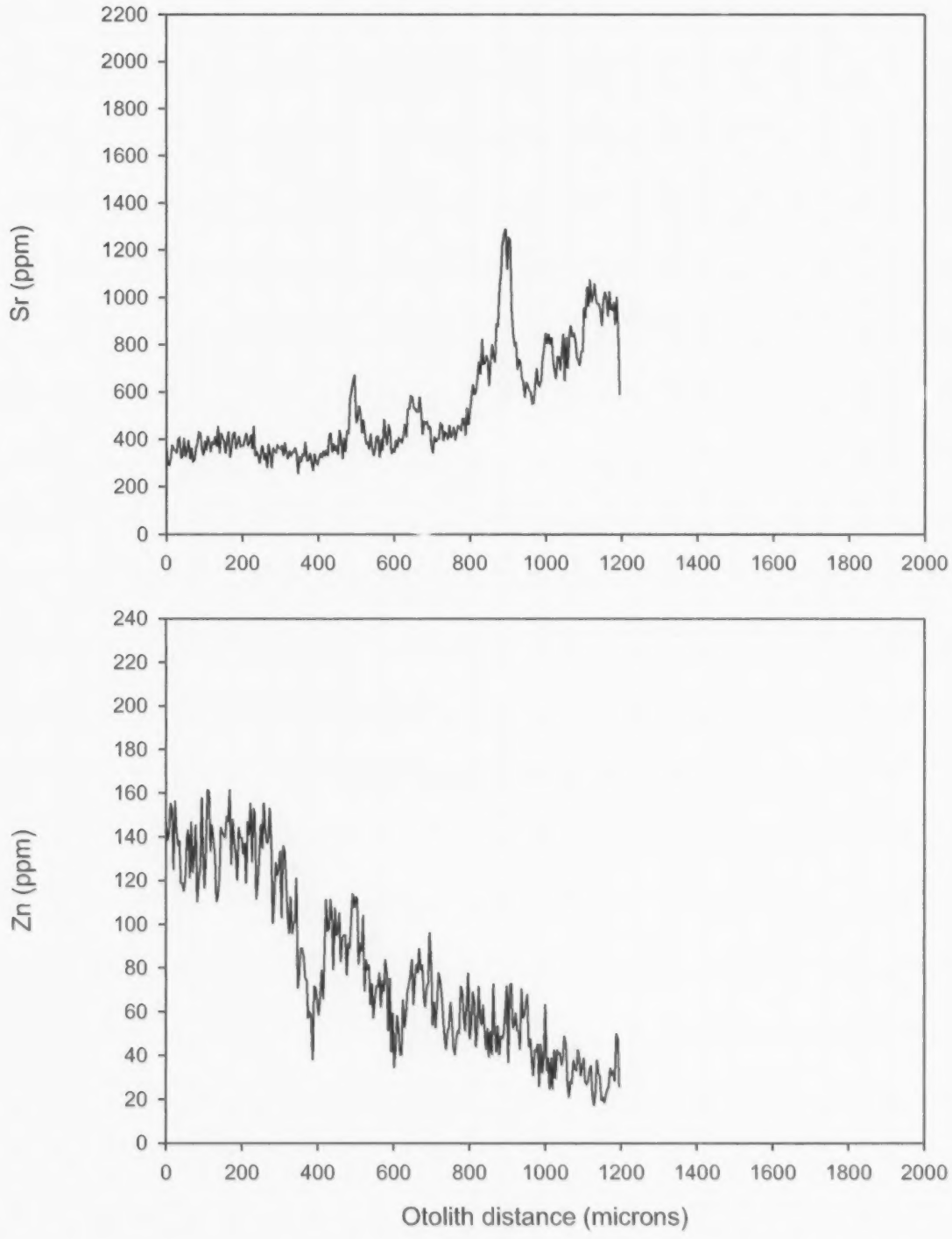

Figure 48. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#49056, 273 mm, 172 g, male, 14 yr) caught in Rambow Hill Lake, July 27-28, 2002.

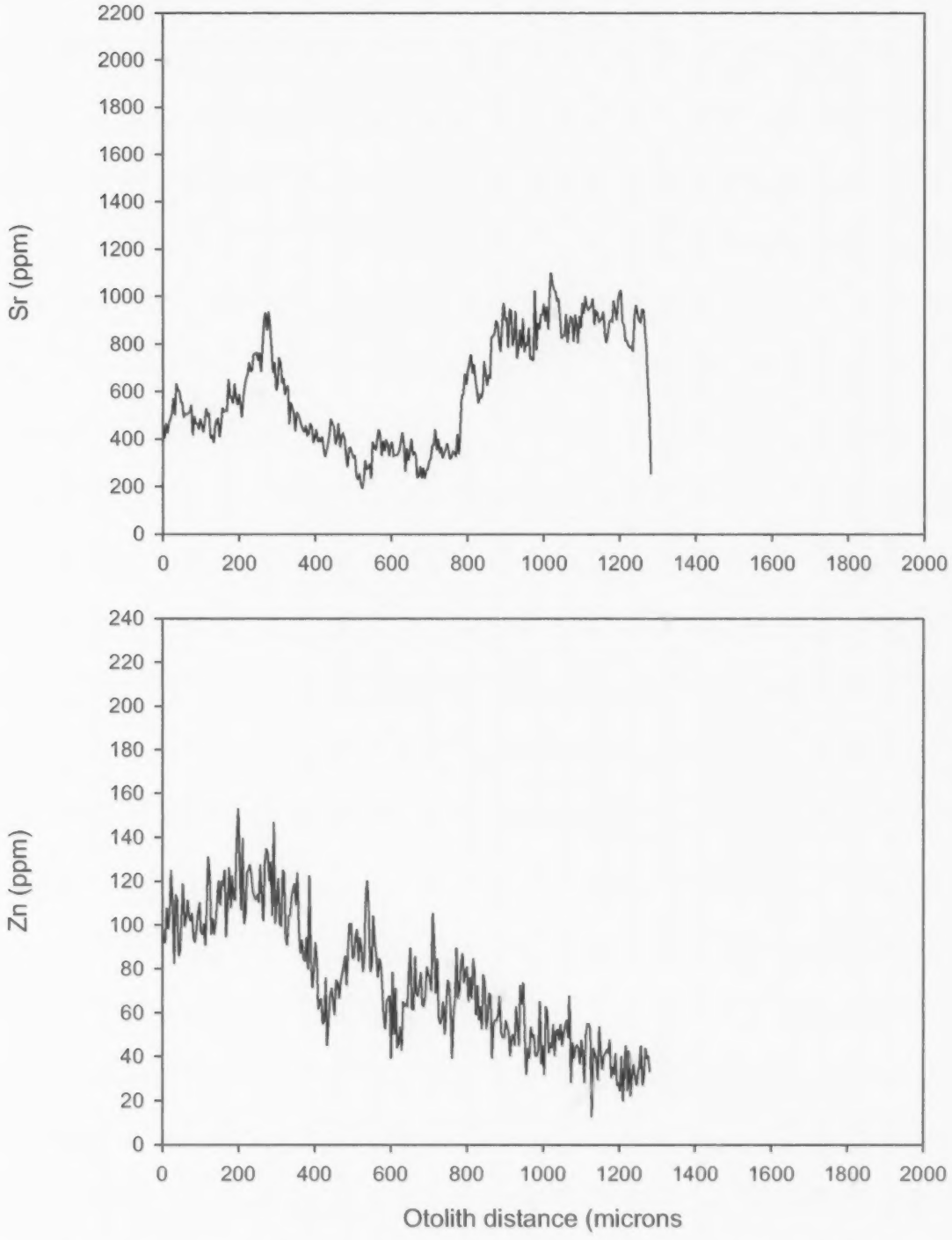

Figure 49. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#49057, 251 mm, 149 g, female, 14 yr) caught in Rambow Hill Lake, July 27-28, 2002.

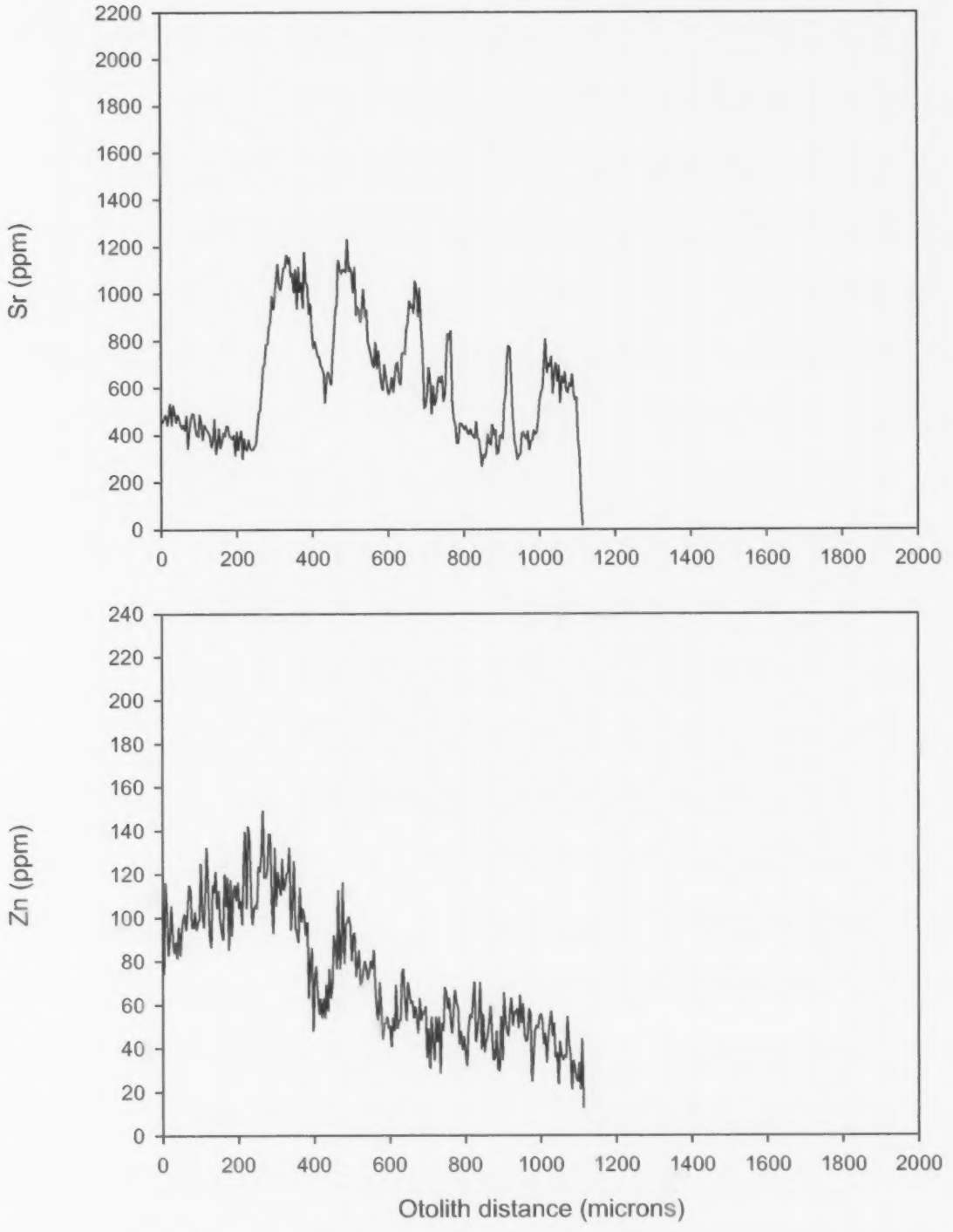

Figure 50. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#49074, 242 mm, 133 g, female, 8 yr) caught in Rambow Hill Lake, July 27-28, 2002.

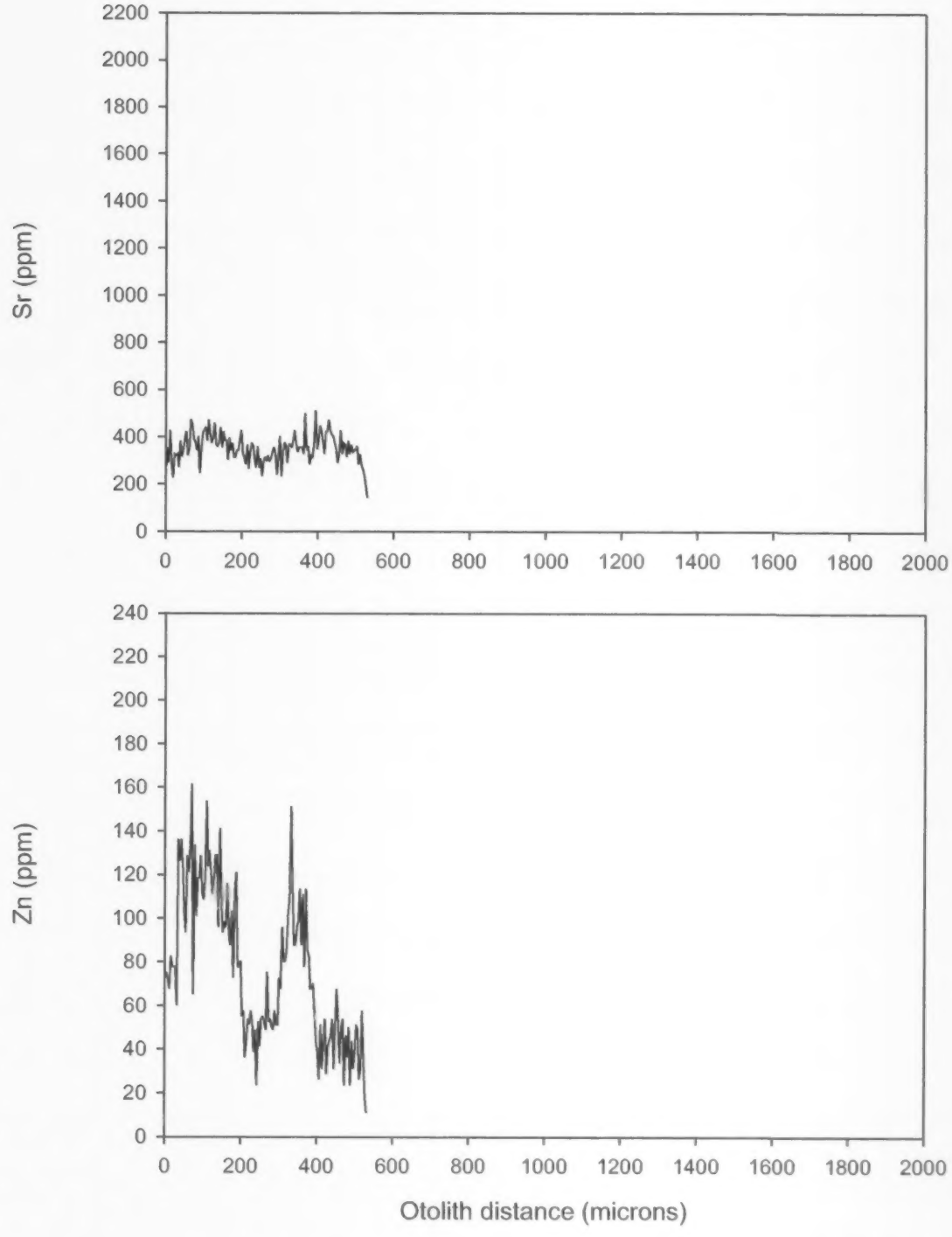

Figure 51. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47395, 98 mm, 9 g, male, 3 yr) caught in Turnabout Lake, August 10, 2001.

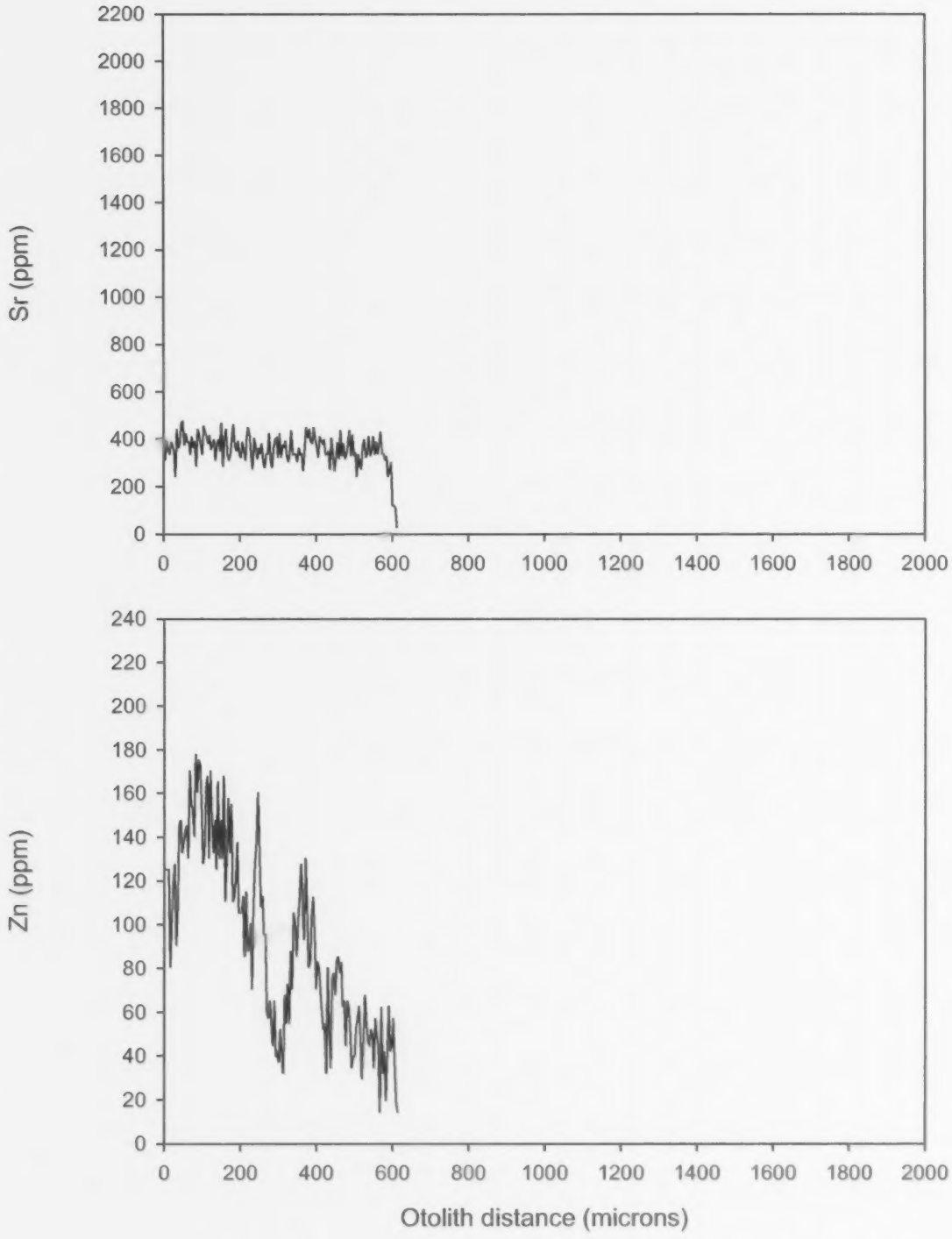

Figure 52. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47396, 96 mm, 10 g, no sex recorded, 3 yr) caught in Turnabout Lake, August 10, 2001.

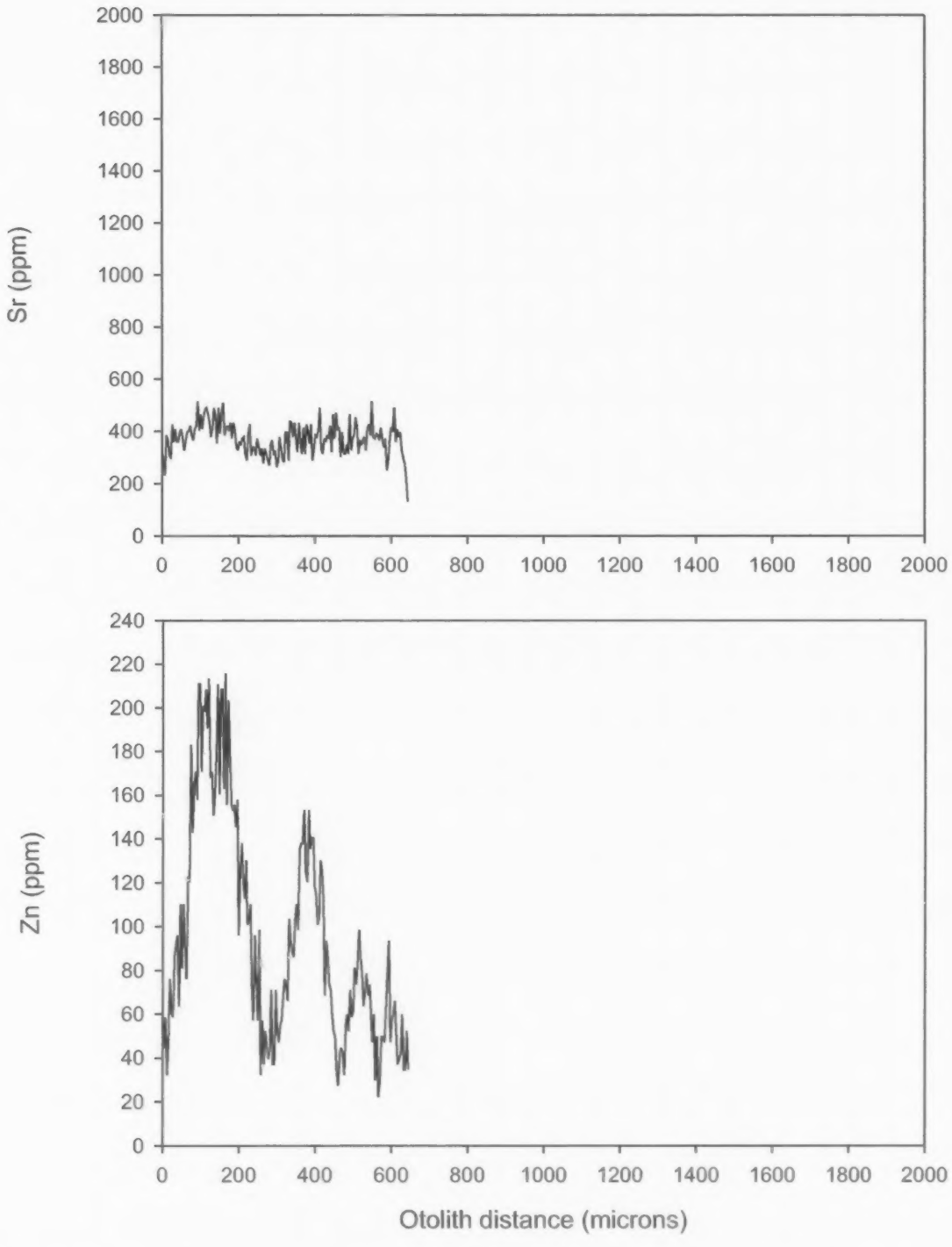

Figure 53. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47397, 135 mm, 26 g, male, 4 yr) caught in Turnabout Lake, August 8, 2001.

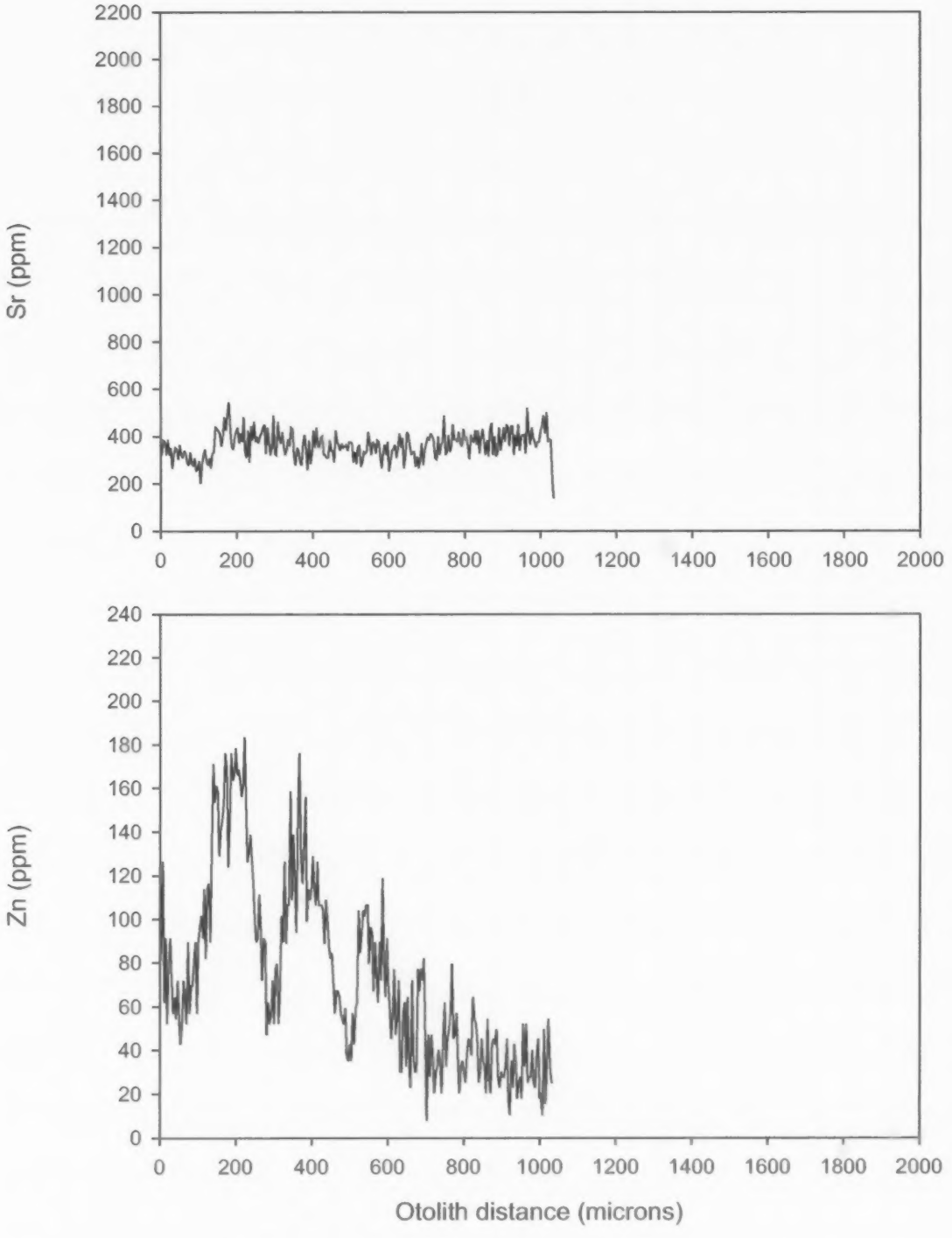

Figure 54. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47398, 178 mm, 46 g, male, 13 yr) caught in Turnabout Lake, August 10, 2001.

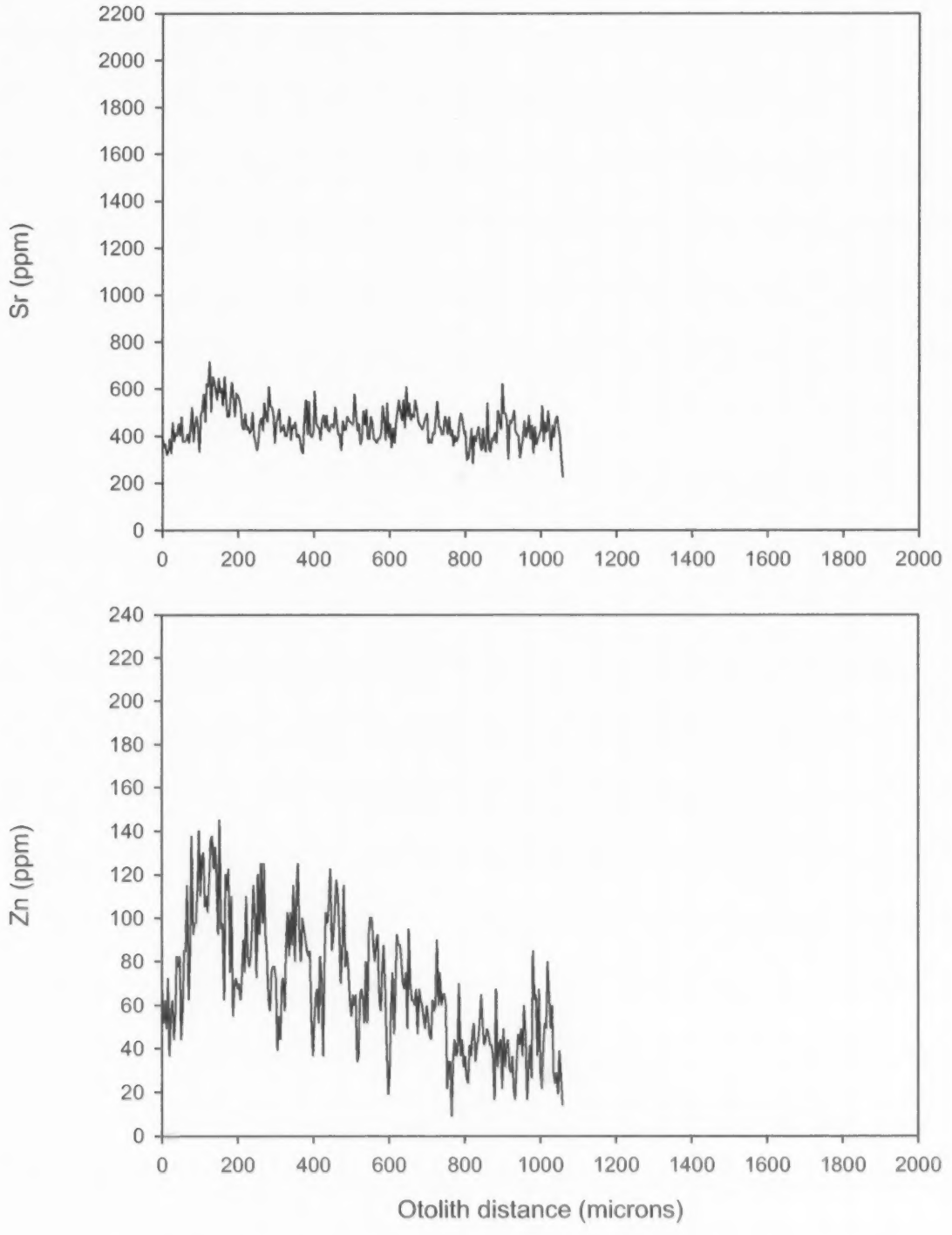

Figure 55. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47399, 263 mm, 180 g, female, 13 yr) caught in Turnabout Lake, August 10, 2001.

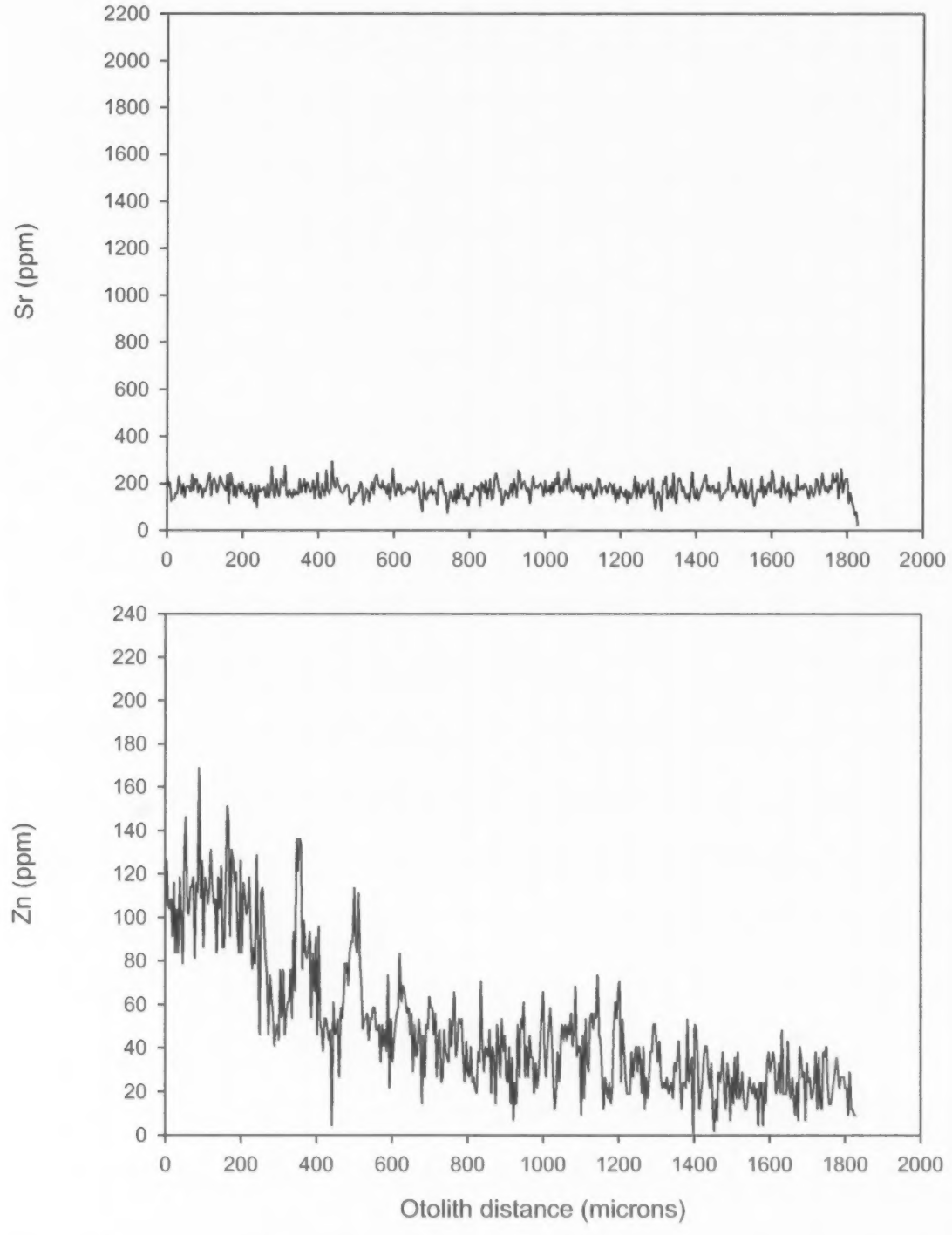

Figure 56. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47322, 463 mm, 870 g, male, 33 yr) caught in Upper Beaufort Lake, August 10, 2001.

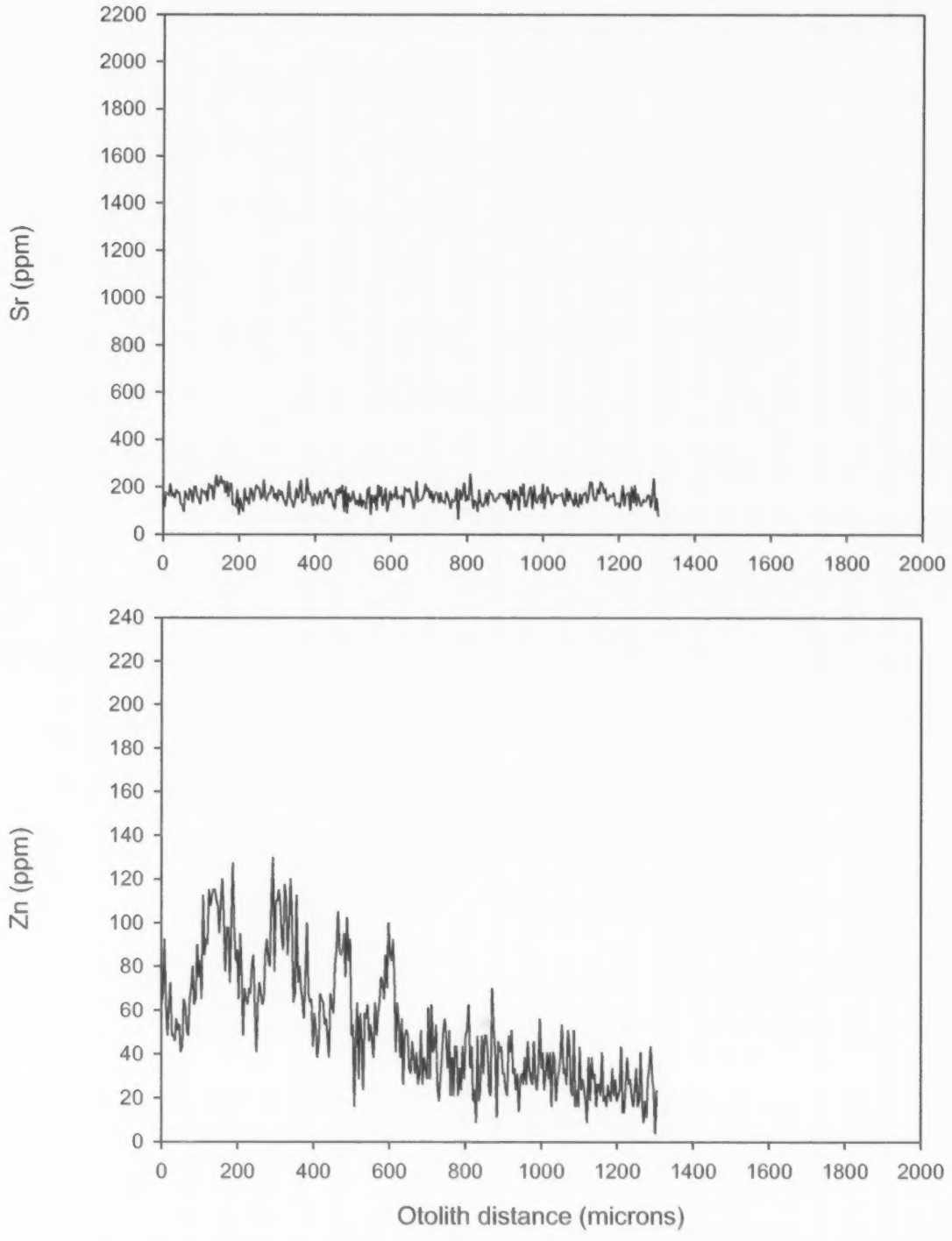

Figure 57. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47323, 479 mm, 1090 g, male, 23 yr) caught in Upper Beaufort Lake, August 10, 2001.

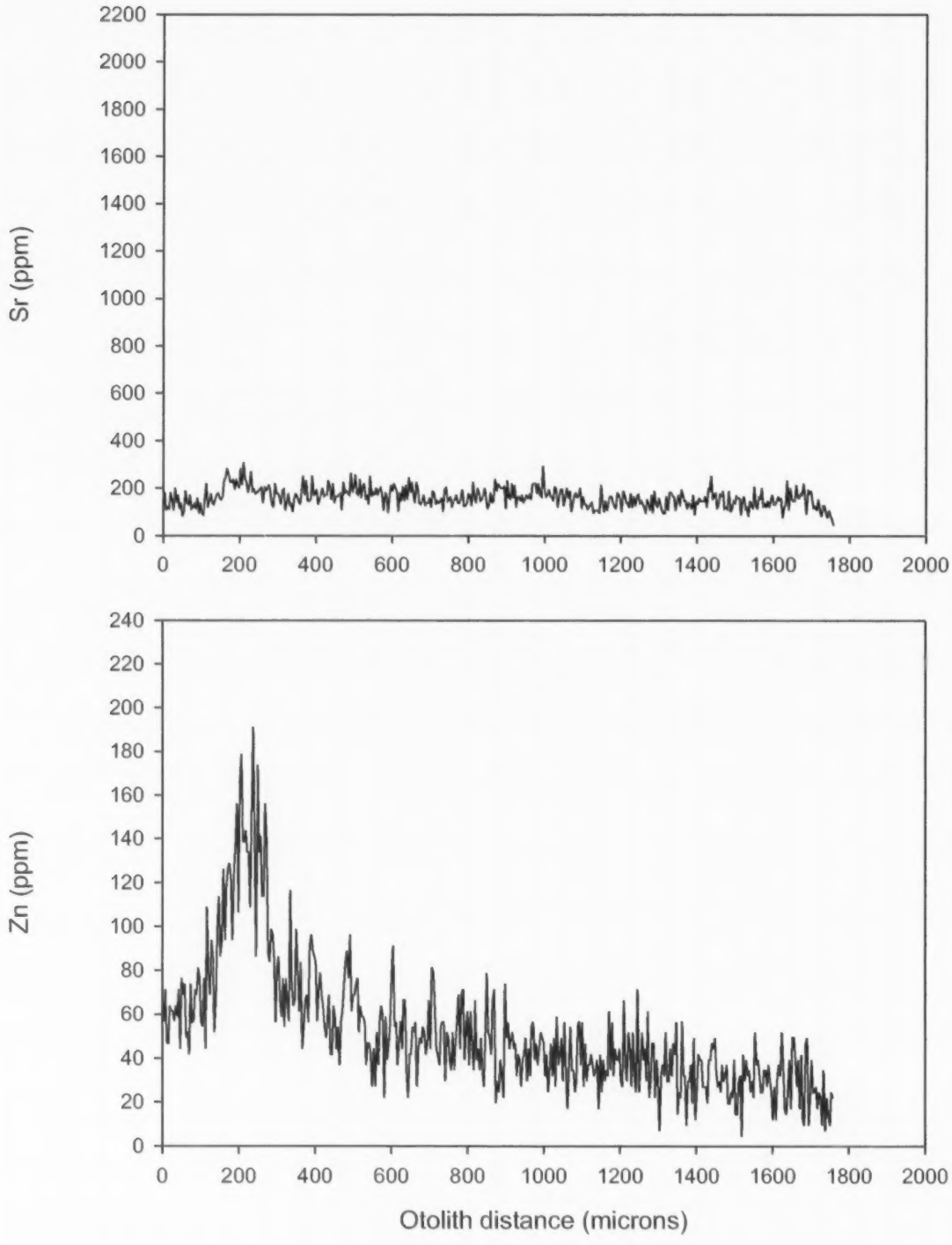

Figure 58. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47324, 495 mm, 1080 g, female, 20 yr) caught in Upper Beaufort Lake, August 10, 2001.

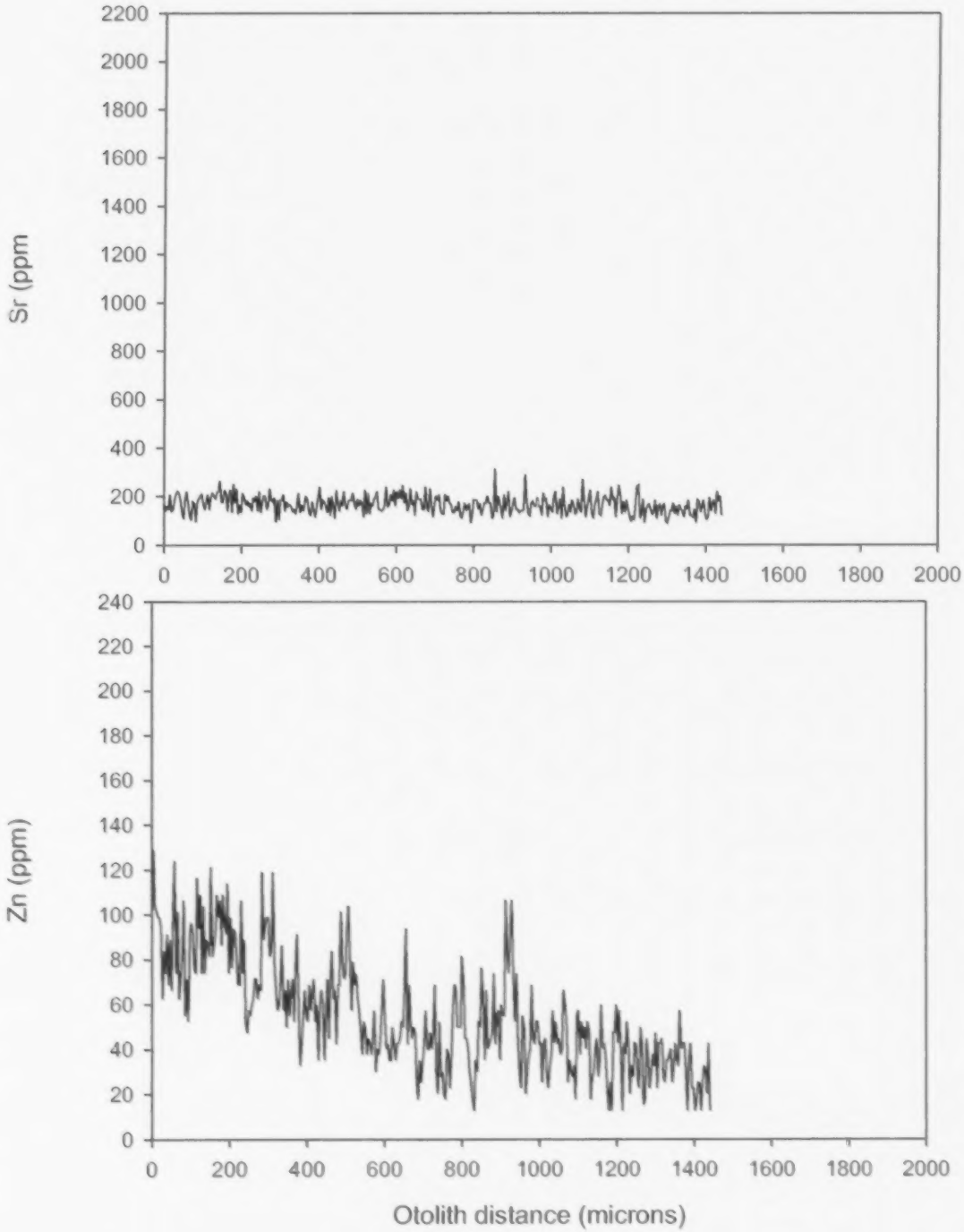

Figure 59. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47354, 371 mm, 450 g, female, 18 yr) caught in Upper Beaufort Lake, August 10, 2001.

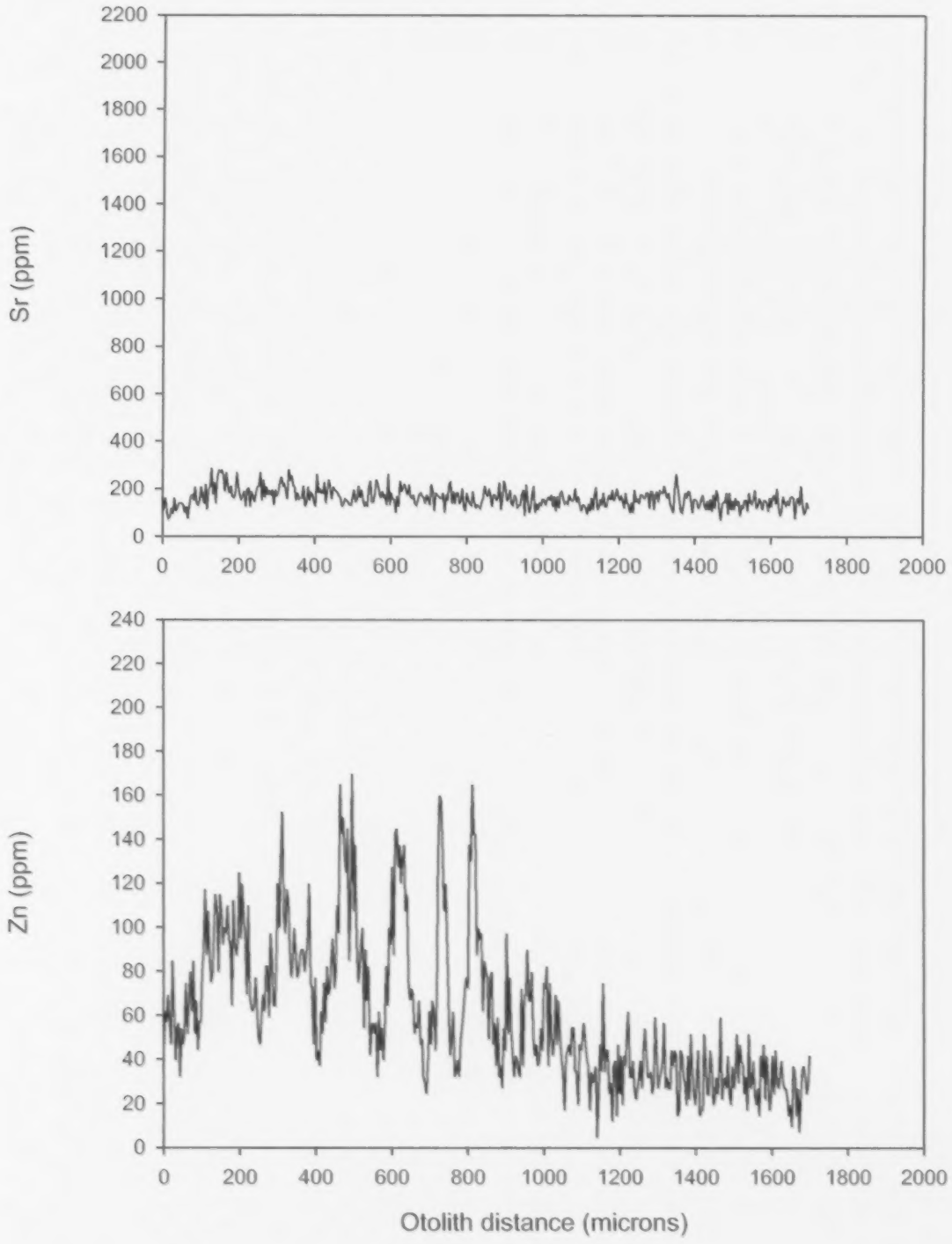

Figure 60. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47357, 545 mm, 1700 g, male, 25 yr) caught in Upper Beaufort Lake, August 10, 2001.

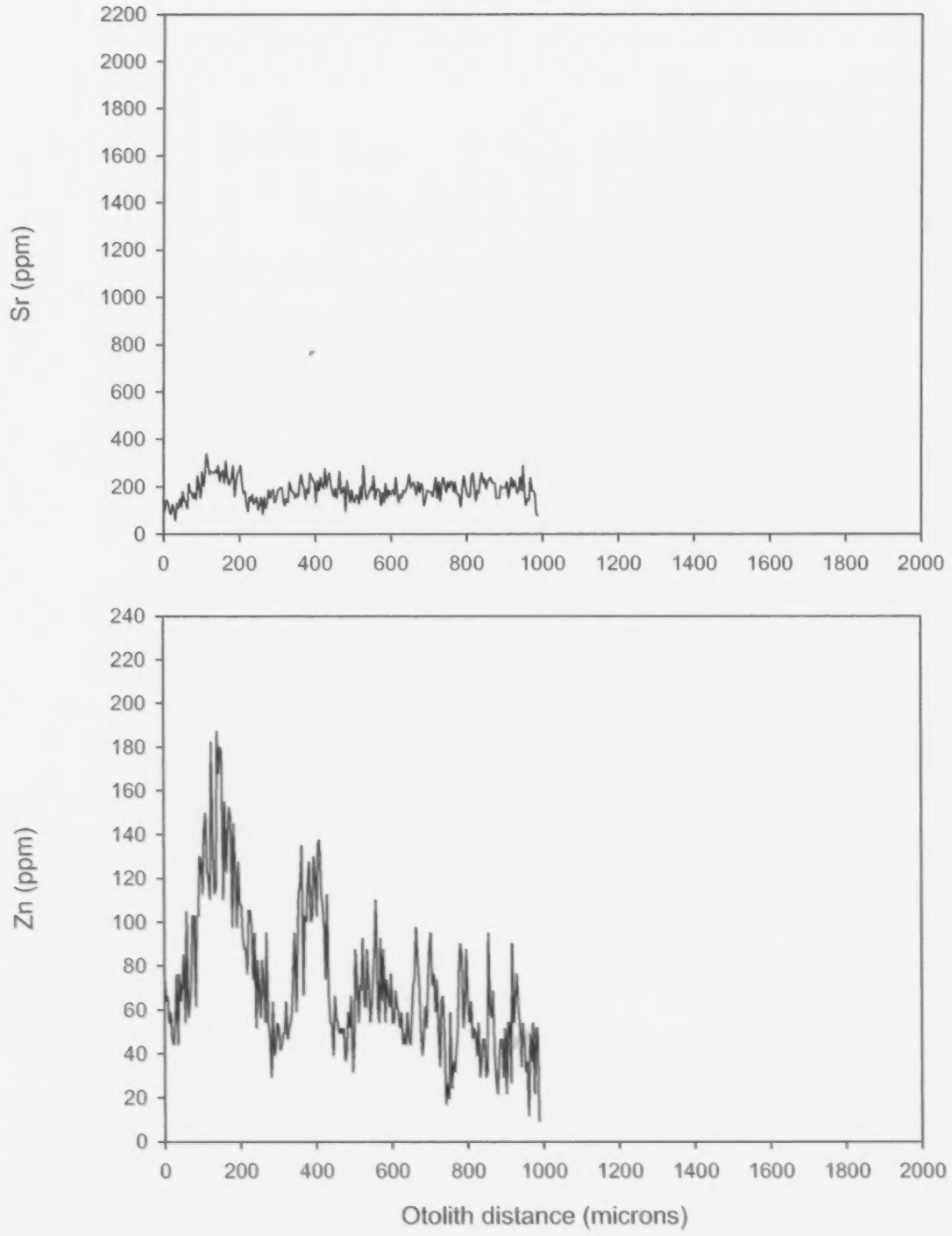

Figure 61. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47359, 289 mm, 210 g, male, 8 yr) caught in Upper Beaufort Lake, August 10, 2001.

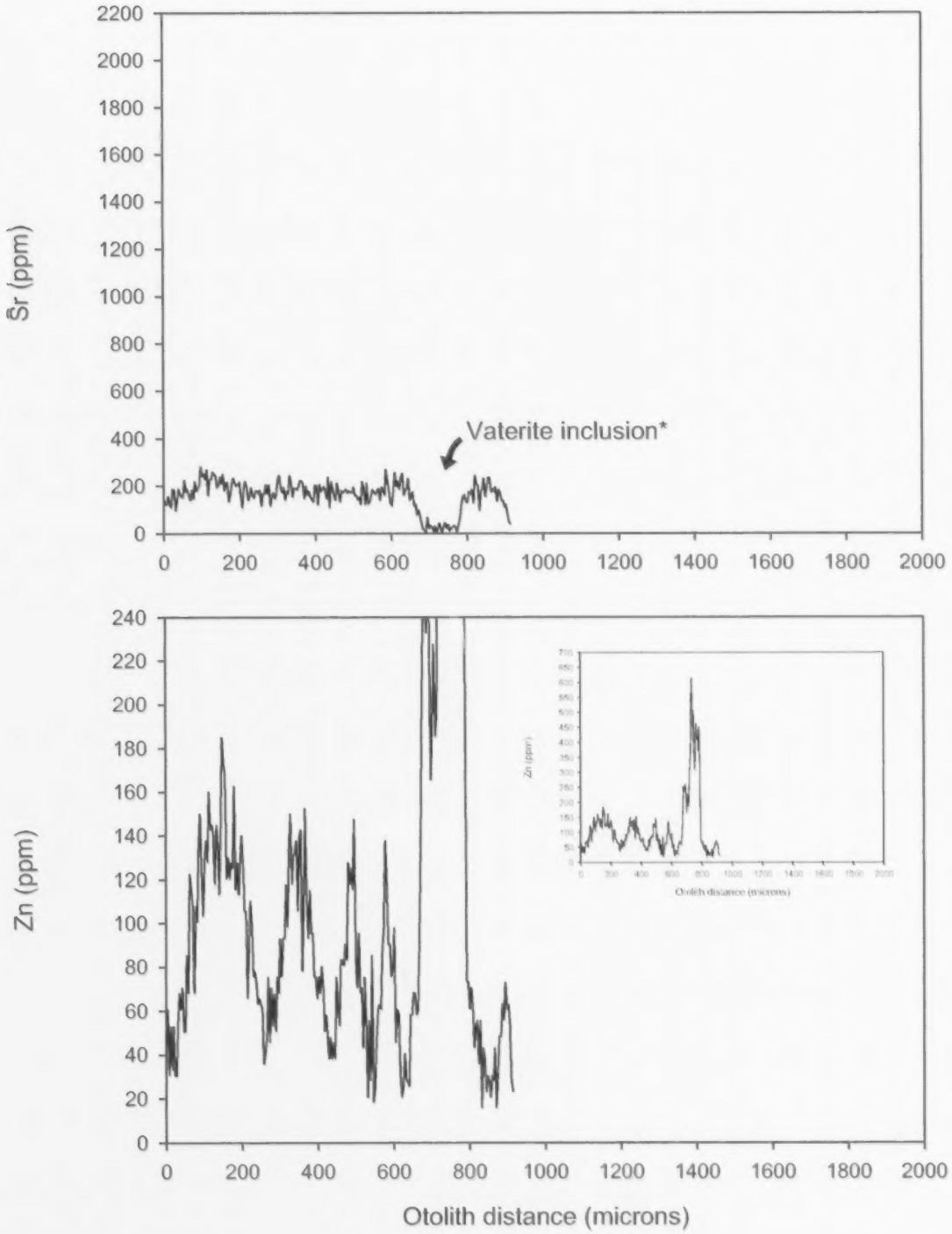

Figure 62. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47360, 236 mm, 110 g, female, 7 yr) caught in Upper Beaufort Lake, August 10, 2001. *See Brown and Severin (1999).

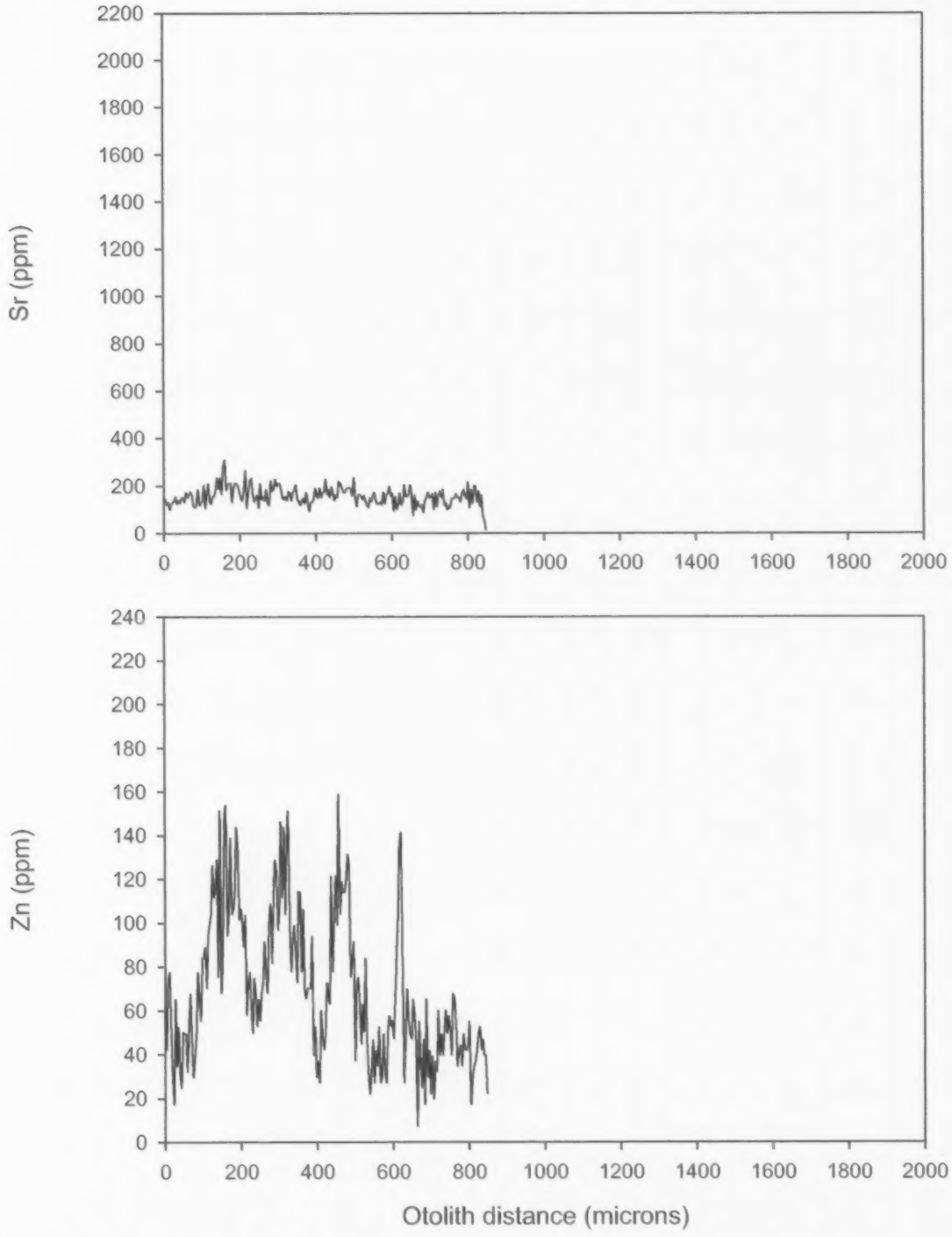

Figure 63. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47361, 187 mm, 55 g, female, 5 yr) caught in Upper Beaufort Lake, August 10, 2001.

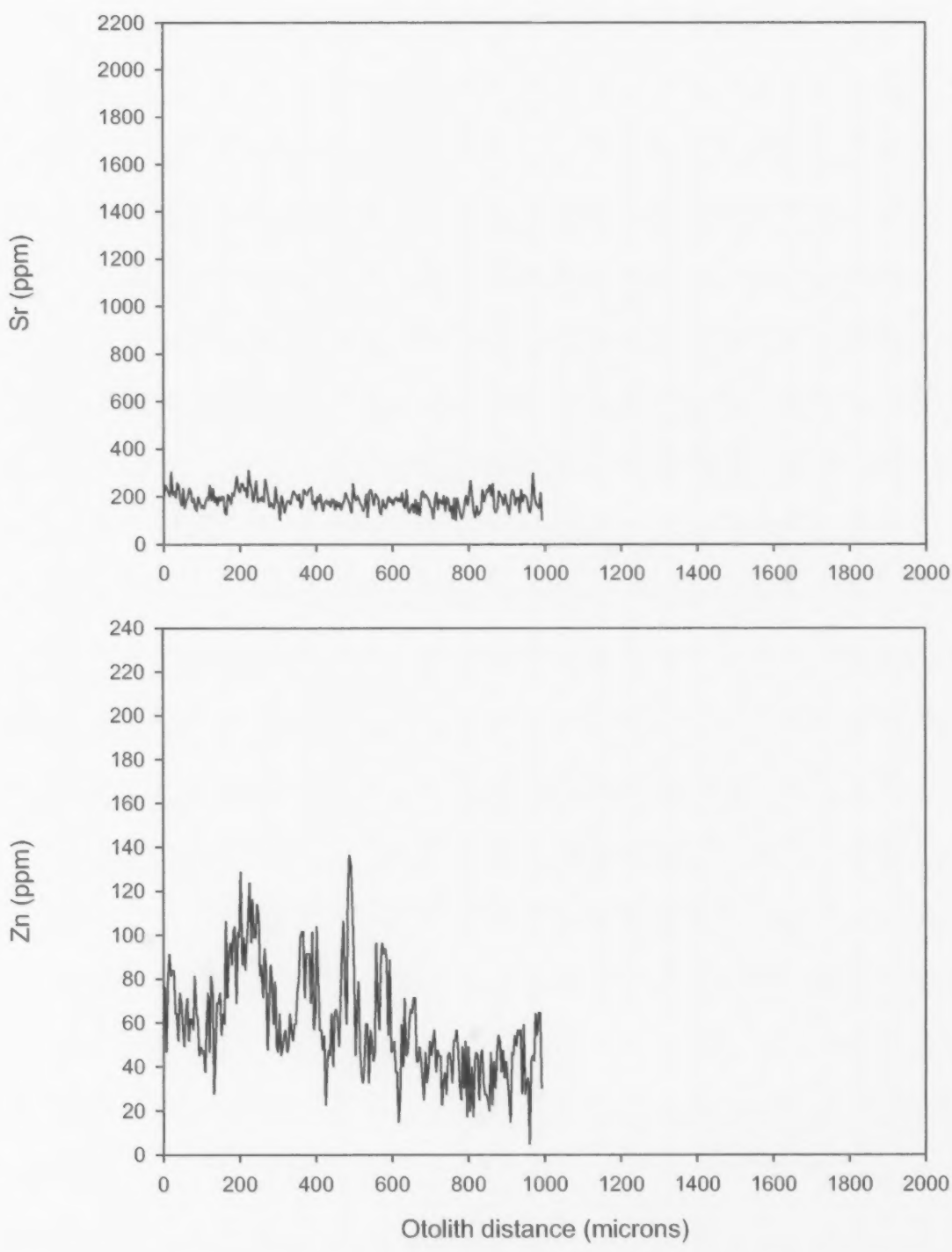

Figure 64. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47362, 224 mm, 88 g, female, 10 yr) caught in Upper Beaufort Lake, August 10, 2001.

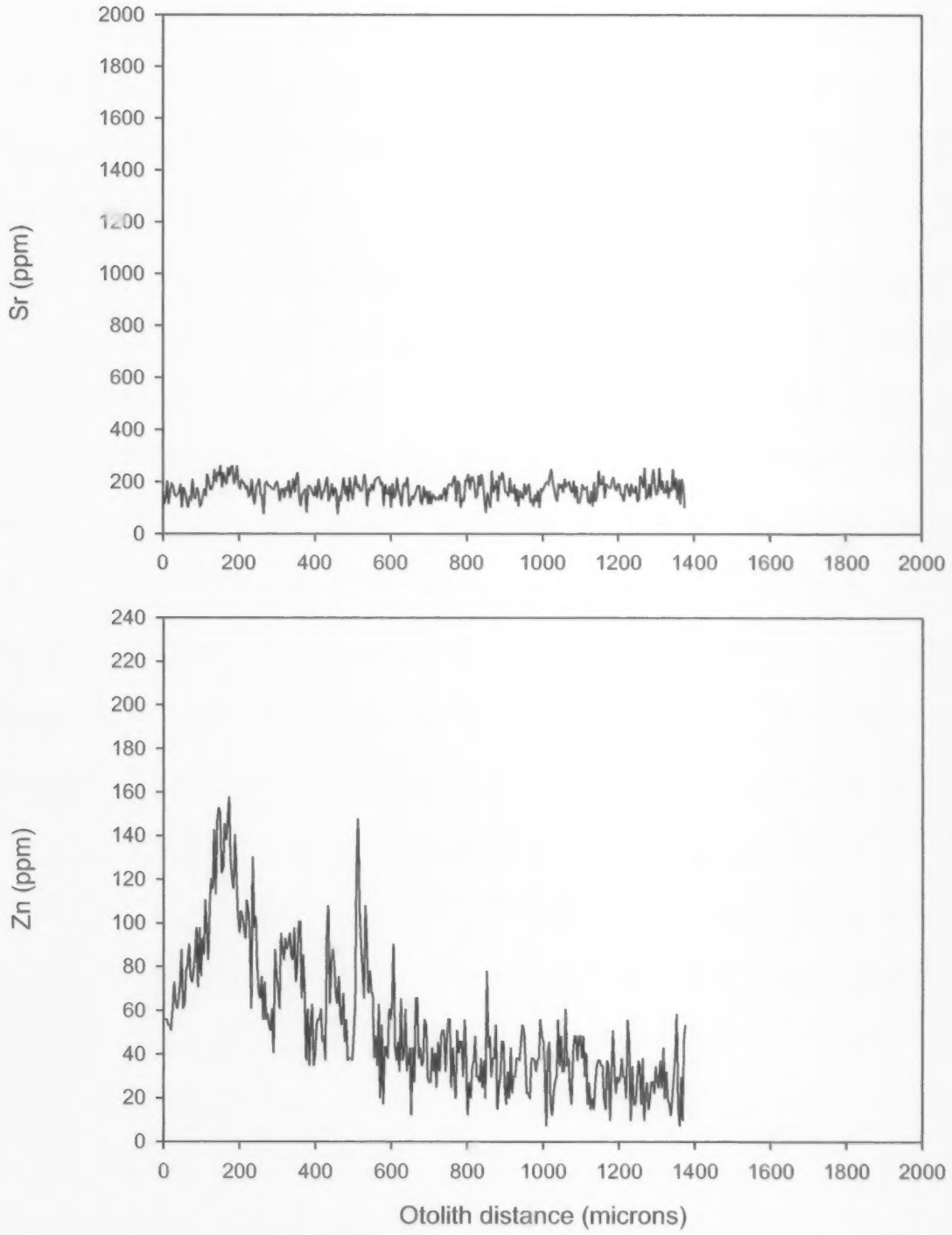

Figure 65. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#47366, 442 mm, 700 g, male, 22 yr) caught in Upper Beaufort Lake, August 10, 2001.

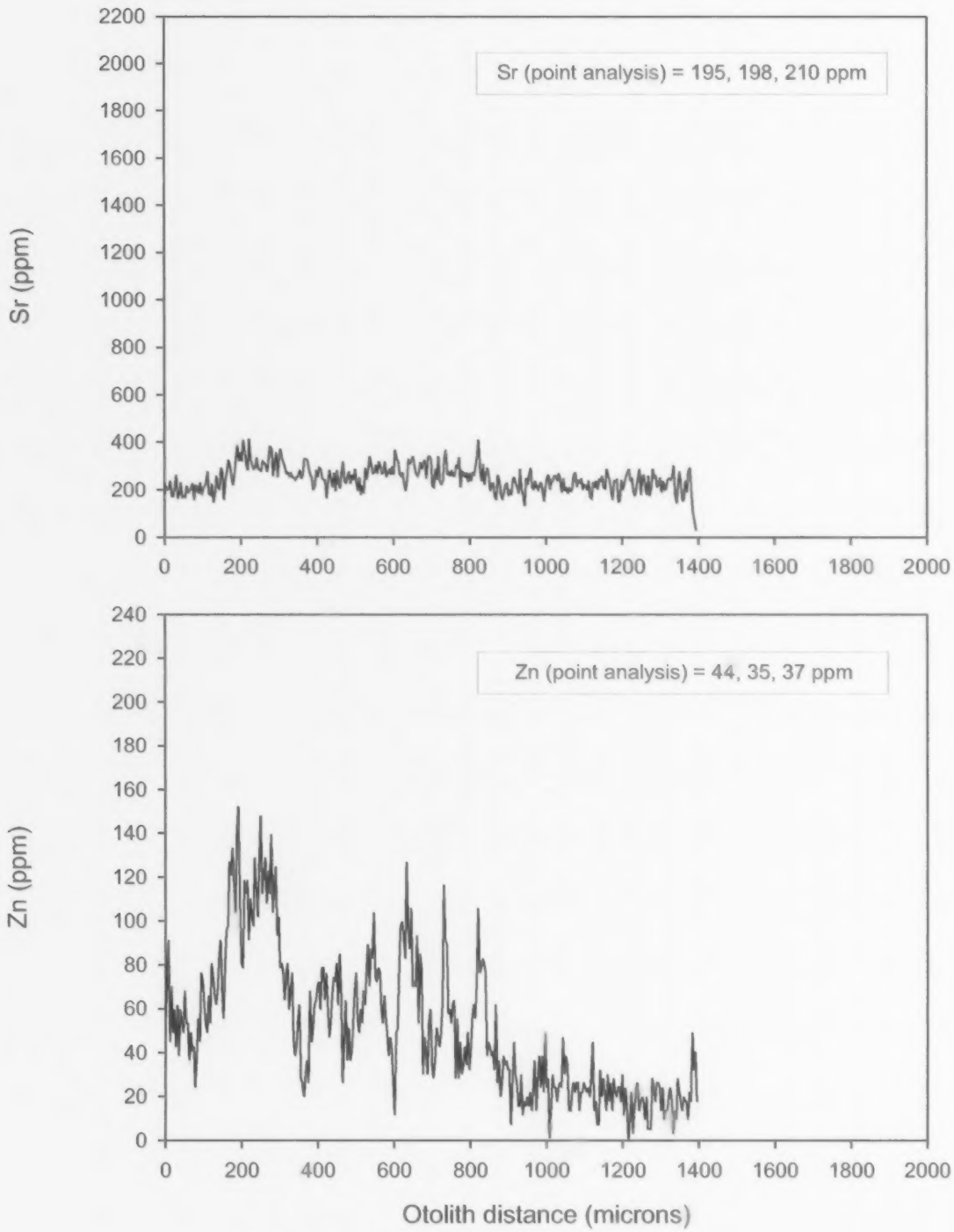

Figure 66. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#34345, 464 mm, 846 g, female, 21 yr) caught in Lake H, summer, 1991. Point analysis results are also indicated.

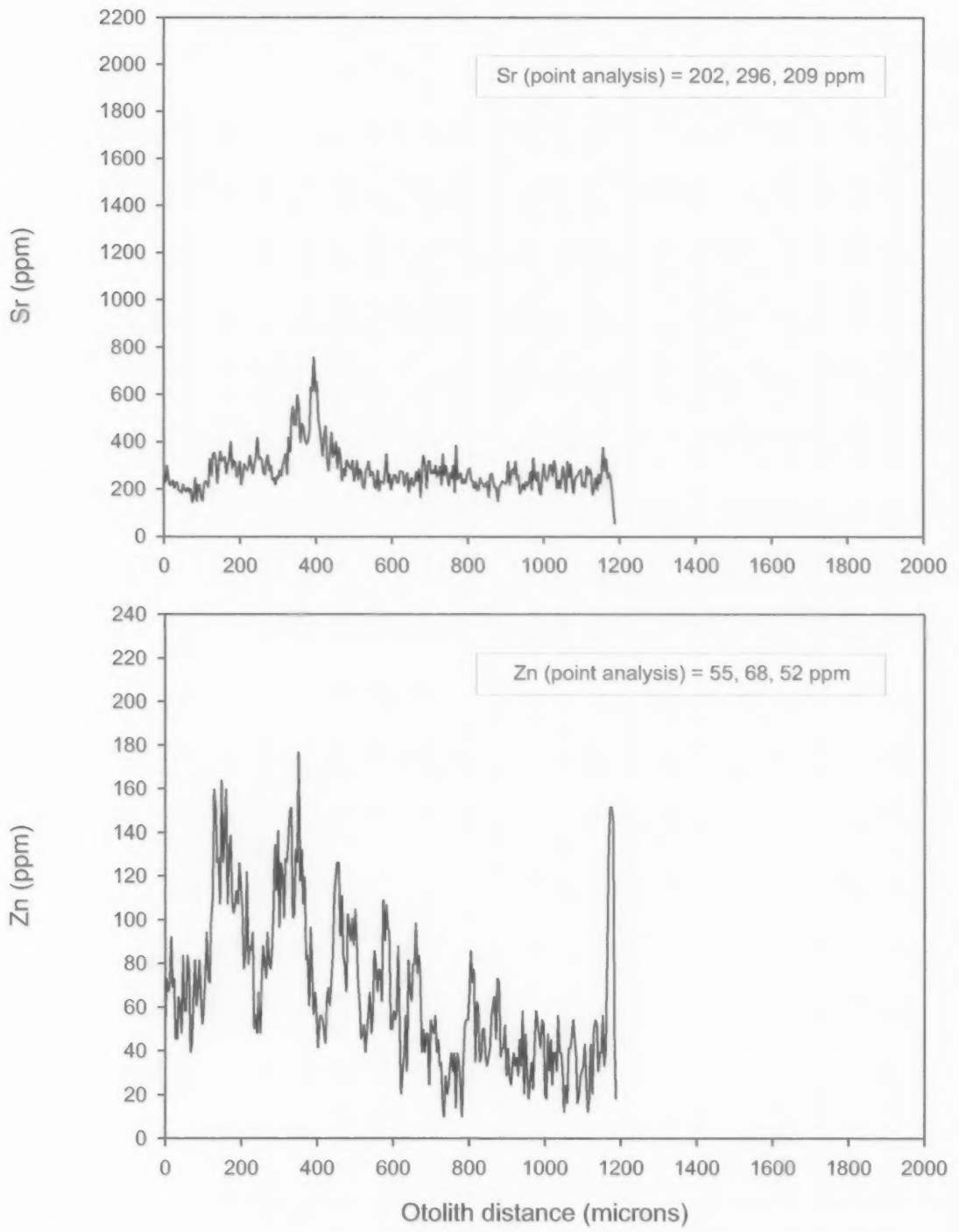

Figure 67. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#34347, 366 mm, 527 g, unknown sex, 15 yr) caught in Lake H, summer, 1991. Point analysis results are also indicated.

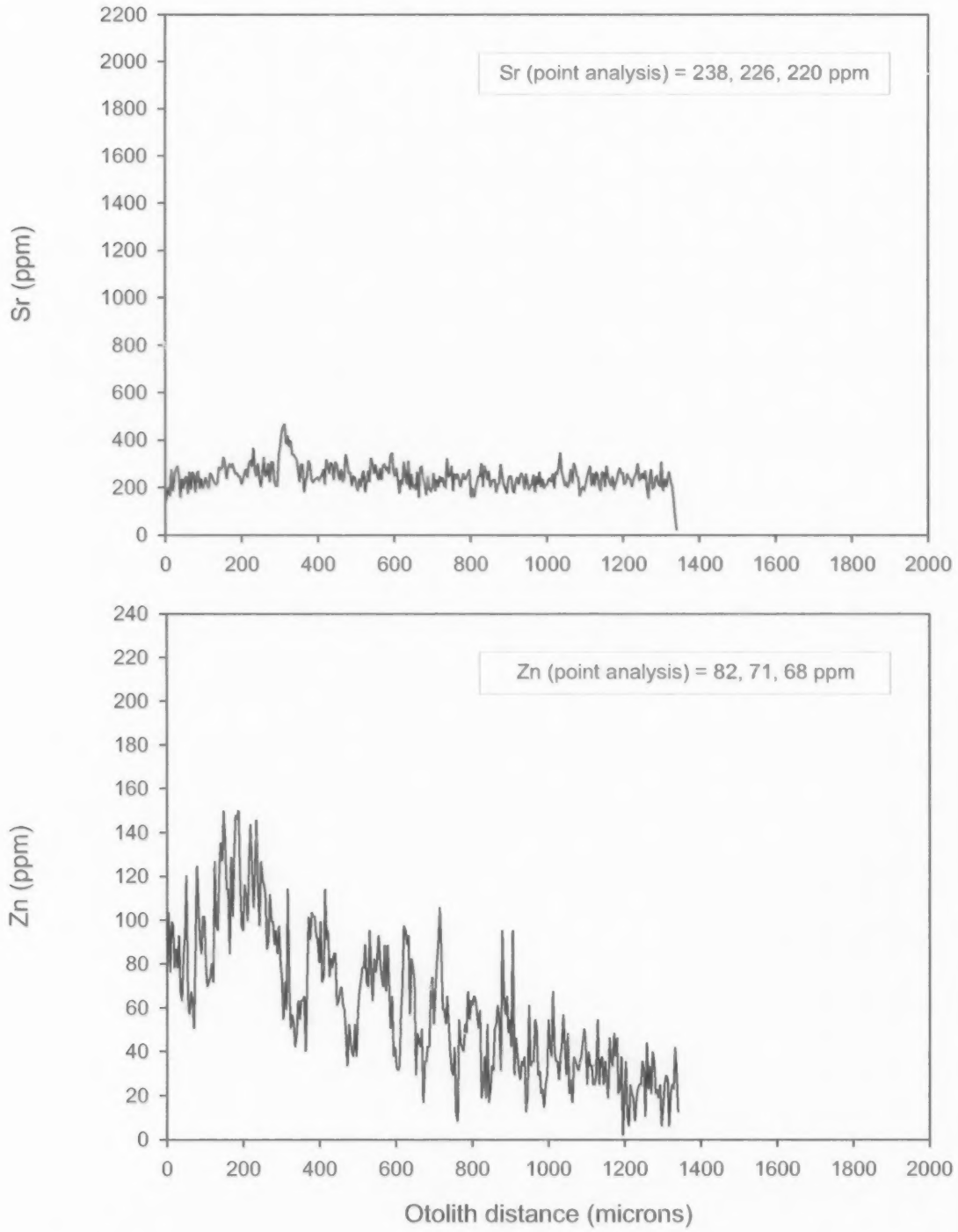

Figure 68. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#34366, 452 mm, 922 g, male, 17 yr) caught in Lake H, summer, 1991. Point analysis results are also indicated.

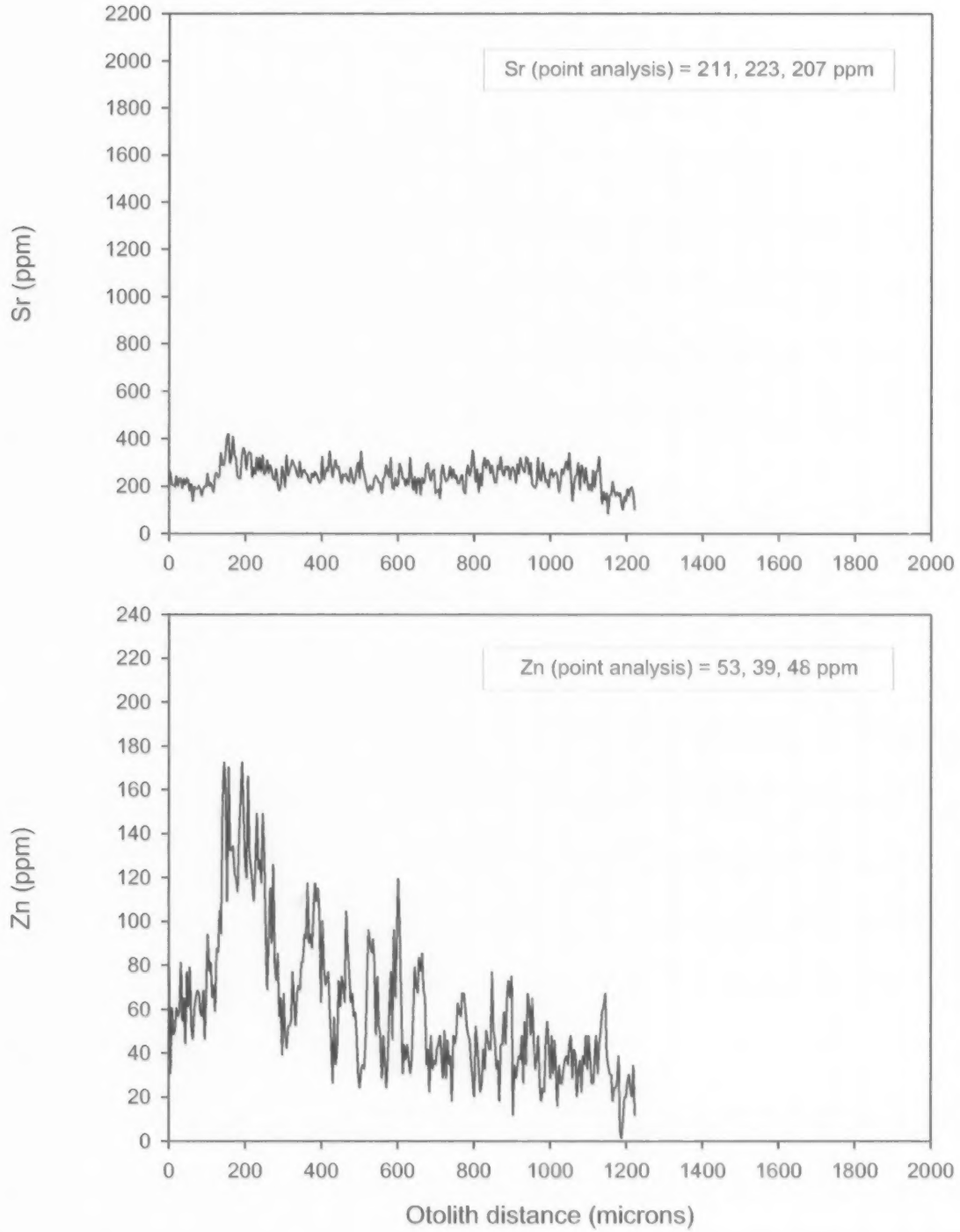

Figure 69. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#34367, 452 mm, 955 g, female, 21 yr) caught in Lake H, summer, 1991. Point analysis results are also indicated.

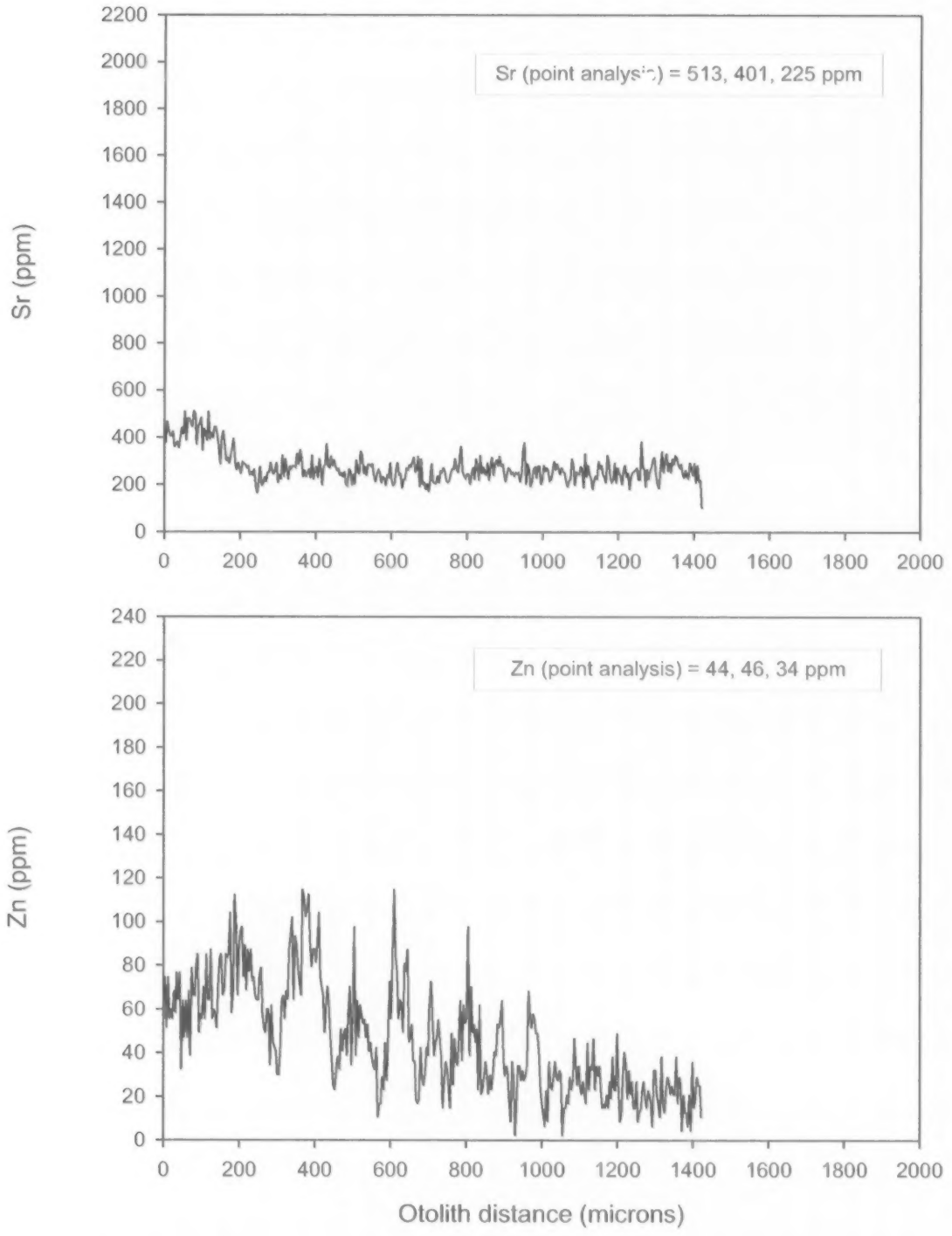

Figure 70. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#34368, 516 mm, 1506 g, male, 18 yr) caught in Lake H, summer, 1991. Point analysis results are also indicated.

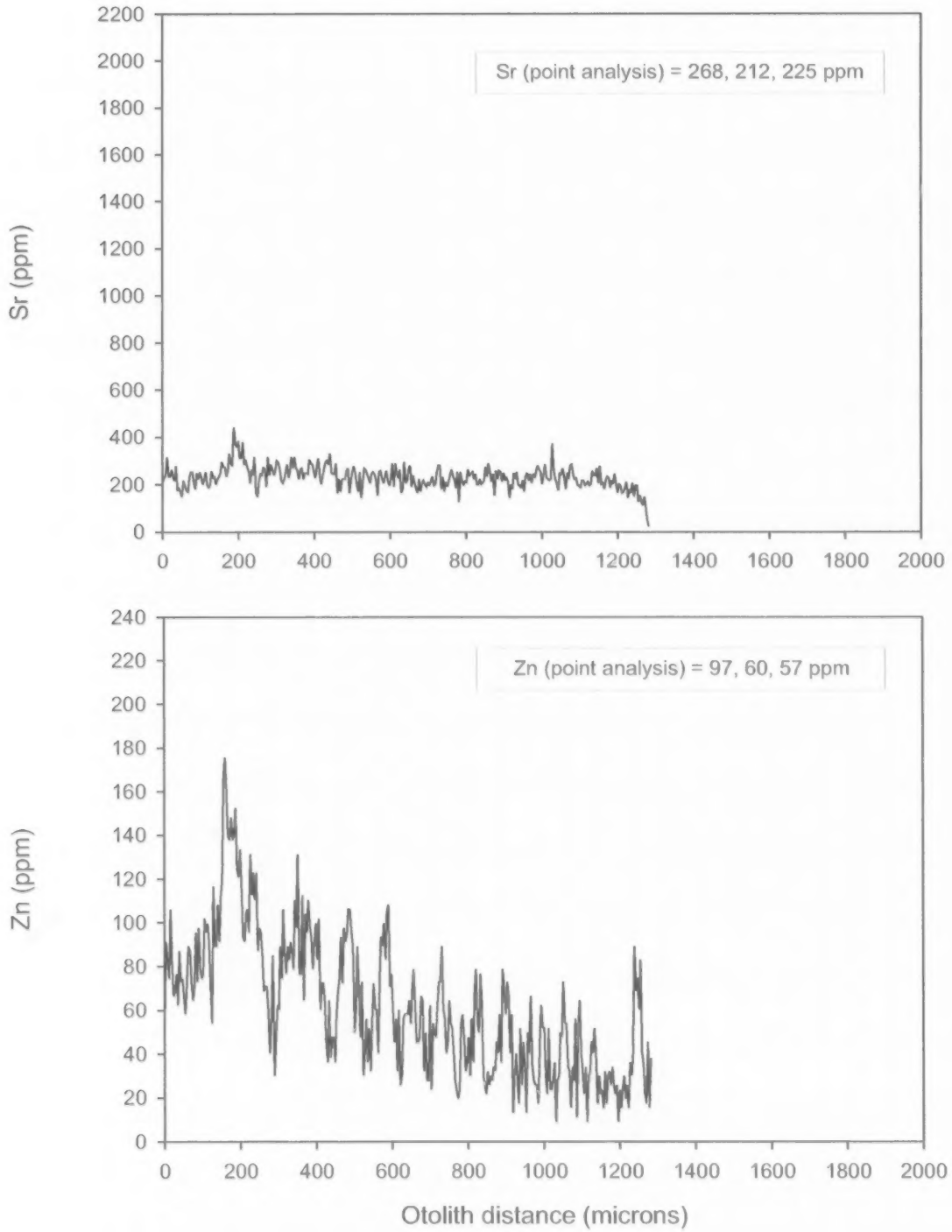

Figure 71. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#34371, 363 mm, 487 g, female, 18 yr) caught in Lake H, summer, 1991. Point analysis results are also indicated.

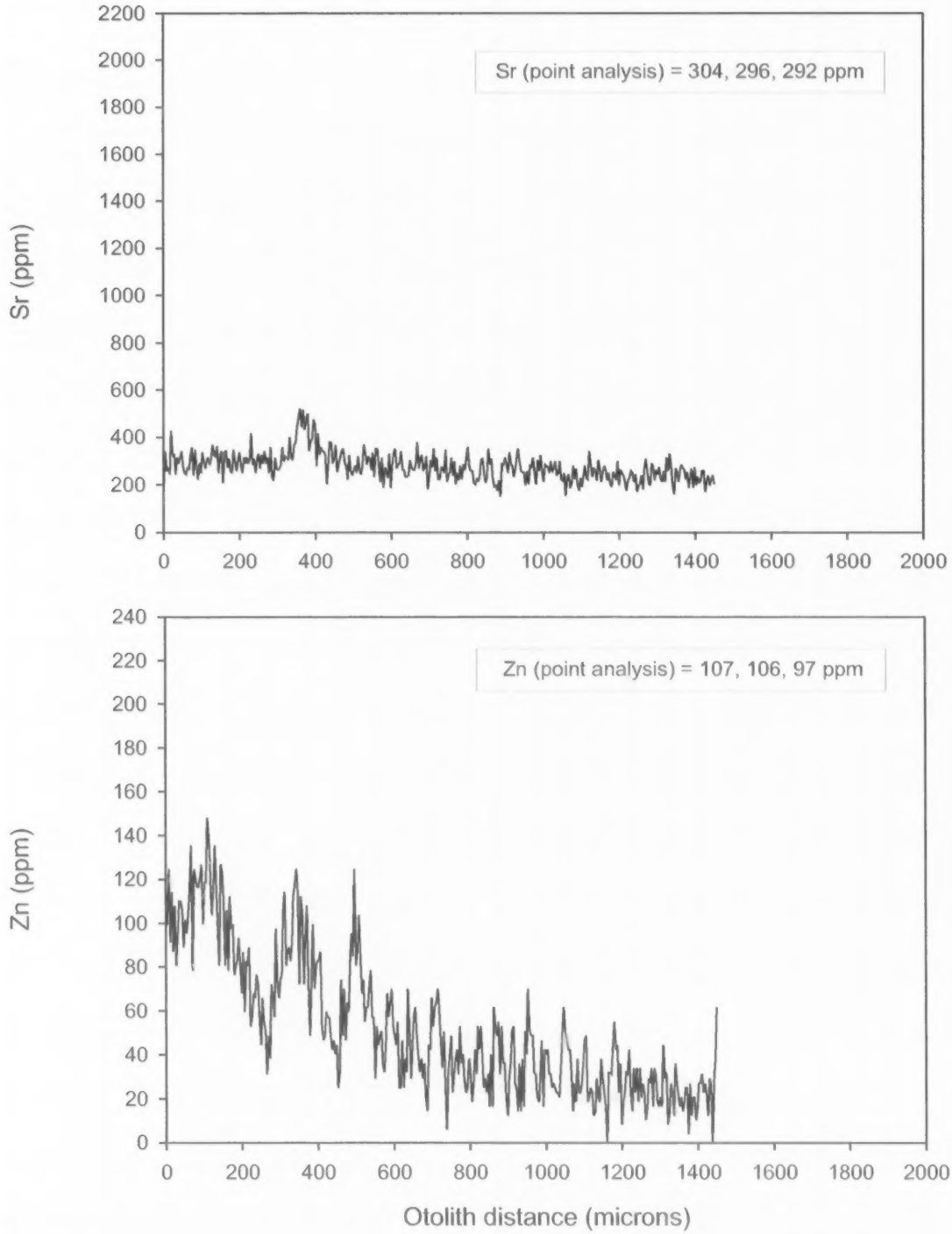

Figure 72. Strontium (top) and zinc (bottom) profiles from a scanning proton microprobe line-scan of an otolith from an Arctic char (#34373, 454 mm, 952 g, male, 23 yr) caught in Lake H, summer, 1991. Point analysis results are also indicated.